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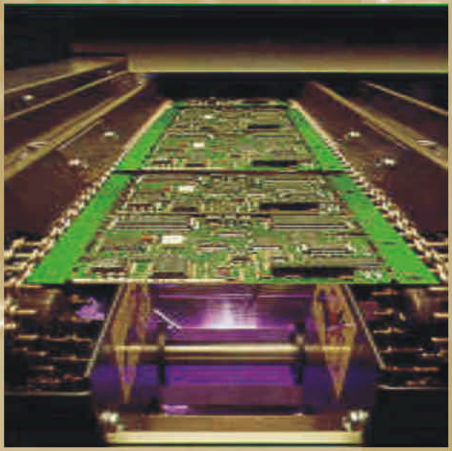

Solders in Electronics: A Life Cycle Assessment

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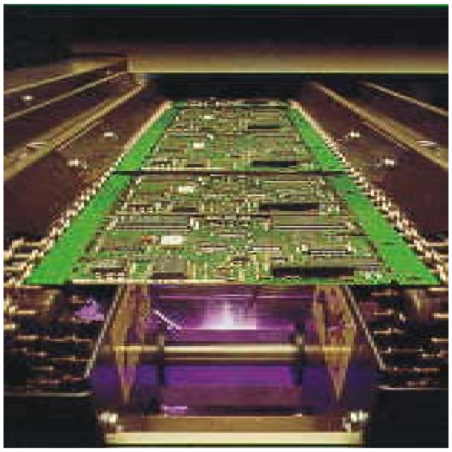

Solders in Electronics: A Life-Cycle Assessment

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Acronyms and Abbreviations

Ag	silver
Amt	amount
AP	acidification potential
Bi	Bismuth
BOD	biological oxygen demand
BOM	bill of materials
BSA	bismuth-tin-silver
CAAA	Clean Air Act Amendments
cc	cubic centimeters
CFC	chlorofluorocarbon
CFC-11	trichlorofluromethane
CFC-12	dichlorodifluoromethane
CFC-13	chlorotrifluromethane
CFC-114	dichlorotetrafluorethane
CHEMS	Chemical Hazard Evaluation for Management Strategies
COD	chemical oxygen demand
CO_2	carbon dioxide
Cu	Copper
D	density
DEAM	Database for Environmental Analysis and Management
DfE	Design for the Environment
DHHS	Department of Health and Human Services
DQI	data quality indicator
EF	equivalency factor
EFSOT	environmentally friendly soldering technology
EIA	Electronic Industries Alliance
EIA	Energy Information Alliance
EOL	end-of-life
EP	eutrophication potential
EPA	Environmental Protection Agency
EU	European Union
GaBi	life-cycle assessment software tool
GWP	global warming potential
H	heat value
HAP	Hazardous Air Pollutant
HEAST	Health Effects Assessment Summary Tables
HSDB	Hazardous Substances Data Bank
HV	hazard value
IARC	International Agency for Research on Cancer
IPC	Association Connecting Electronics Industries
IPCC	Intergovernmental Panel on Climate Change
IRIS	Integrated Risk Information System
IS	impact score
ISO	International Standards Organization
ITRI	Interconnect Technology Research Institute
kg	kilogram

K_{ow}	octanol water co-efficient
kW	kilowatt
LC	lethal concentration
LC_{50}	lethal concentration to 50 percent of the exposed fish population
LCA	life-cycle assessment
LCI	life-cycle inventory
LCIA	life-cycle impact assessment
LFSP	Lead-Free Solder Project
LNG	liquified natural gas
LOAEL	lowest-observed-adverse-effect levels
LPG	liquified petroleum gas
m^3	cubic meter
MACT	maximum achievable control technology
ME&P	materials extraction and processing
mg	milligrams
MITI	Ministry of International Trade and Industry
MJ	megajoule
MSW	municipal solid waste
N	nitrogen
NCMS	National Center for Manufacturing Sciences
NEMI	National Electronics Manufacturing Initiative
NMVOC	non-methane volatile organic compounds
NOAEL	no-observed-adverse-effect levels
NOEC	no-observed-effect concentration
NOEL	no-observed-effect level
NRR	non-renewable resource
OD	ozone depletion
ODP	ozone depletion potential
OEM	original equipment manufacturer
P	phosphorus
Pb	lead
PI	post-industrial
PM	particulate matter
PM_{10}	particulate matter with an average aerodynamic diameter less than 10 micrometers
PO_4^{3-}	phosphate
POCP	photochemical oxidant creation potential
POTW	publicly-owned treatment works
PWB	printed wiring board
QSAR	quantitative structure-activity relationship
RC	recycled content
RCRA	Resource Conservation and Recovery Act
ROHS	Restriction of Hazardous Substances
RR	renewable resource
RSS	ramp-soak-spike
RTECS	Registry of Toxic Effects of Chemical Substances
SABC	tin-silver-bismuth-copper
SAC	tin-silver-copper

SAR	structure-activity relationship
SETAC	Society of Environmental Toxicology and Chemistry
SF	slope factor
Sn	tin
SnPb	tin-lead
SnCu	tin-copper
SO_2	sulfur dioxide
SPLP	synthetic precipitation leaching procedure
SWL	solid waste landfill
TAL	time above liquidous
TCLP	toxic characteristic leachate procedure
TRI	toxic release inventory
TSP	total suspended particulates
TSS	total suspended solids
UF	University of Florida
UT	University of Tennessee
VOC	volatile organic carbons
WEEE	Waste Electronics and Electronic Equipment
WOE	weight of evidence
Zn	Zinc

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 (°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.

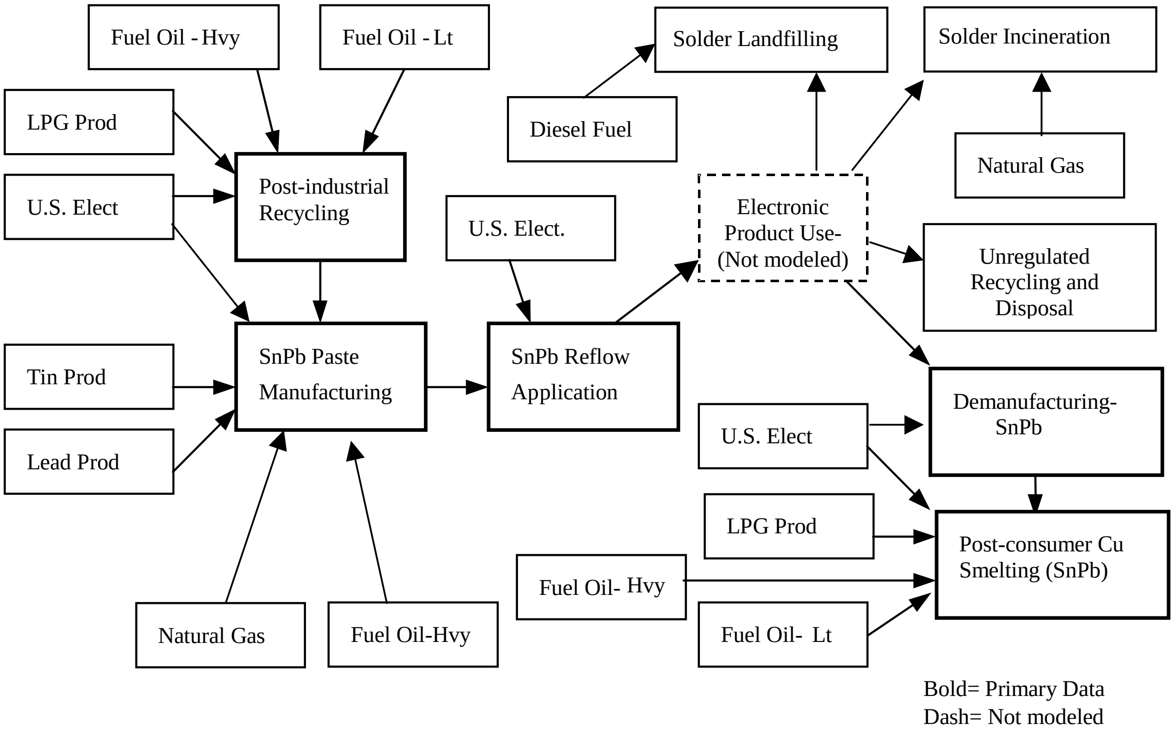

Figure ES-1. SnPb Paste Solder Life-Cycle Processes

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.

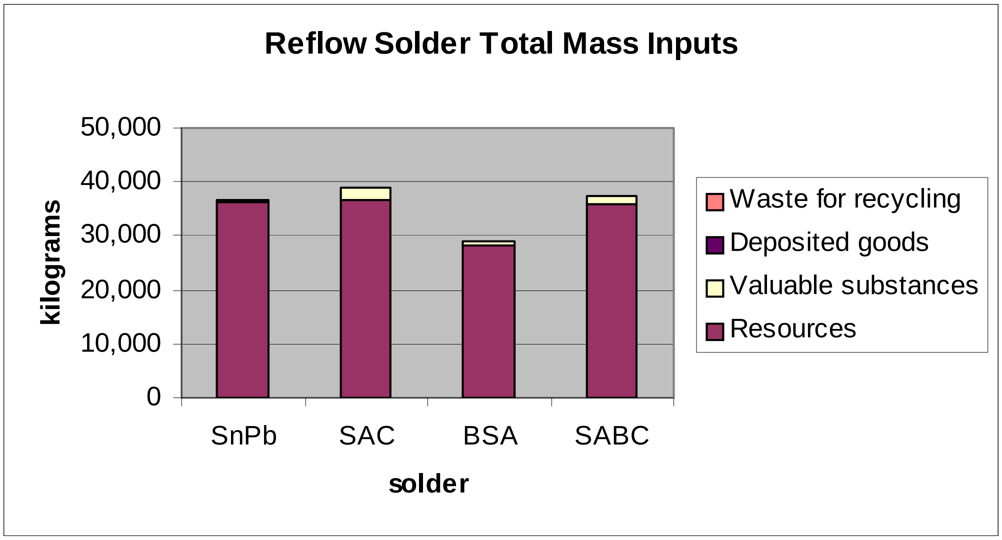

Figure ES-2. Paste Solder Total Mass Inputs

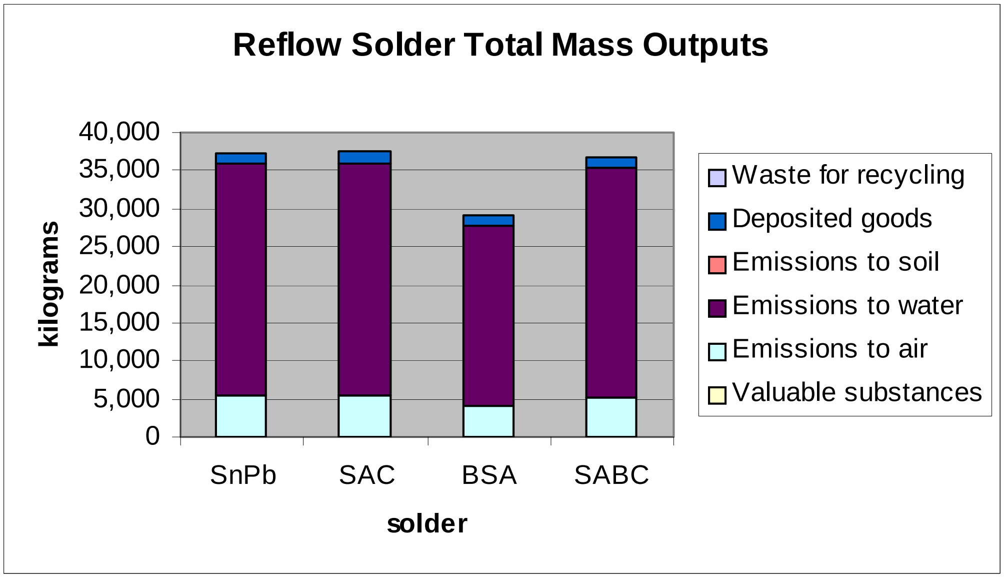

Figure ES-3. Paste Solder Total Mass Outputs

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.

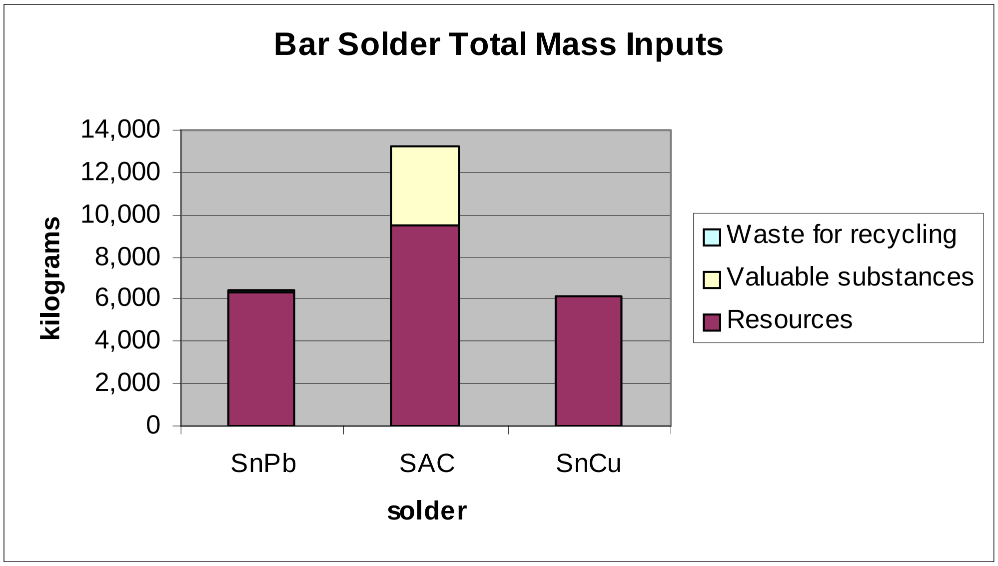

Figure ES-4. Bar Solder Total Mass Inputs

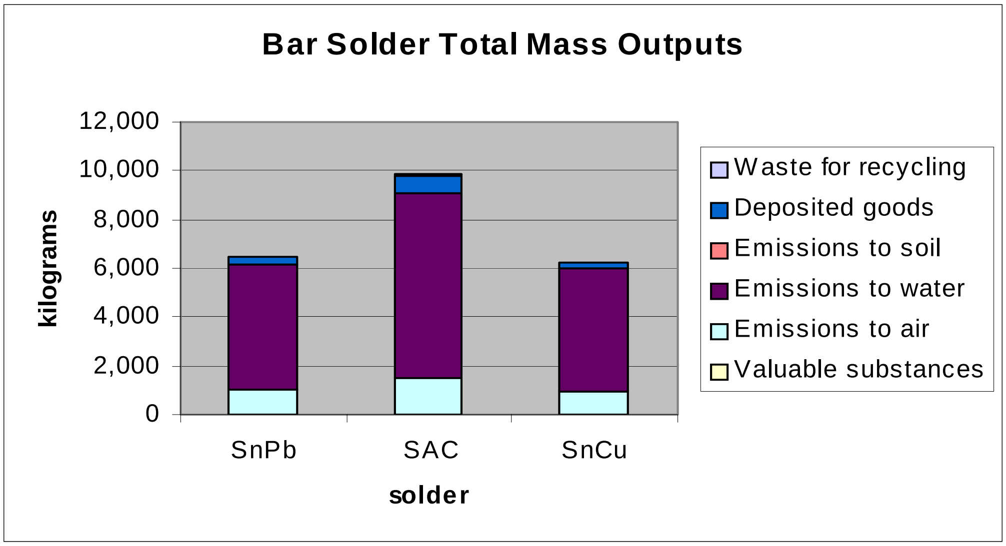

Figure ES-5. Bar Solder Total Mass Outputs

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).

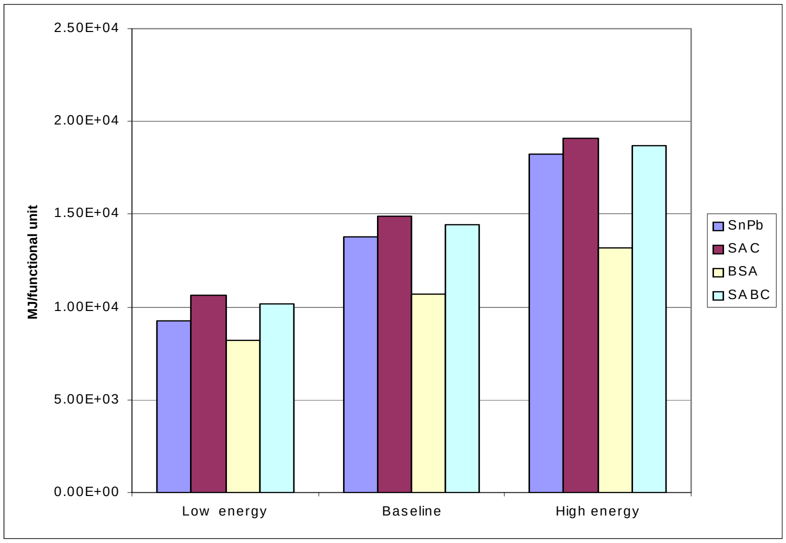

Figure ES-6. Sensitivity Analysis of Energy Consumption during Reflow Solder Application

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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Chapter 1

GOAL DEFINITION AND SCOPE

1.1 INTRODUCTION

This project report presents the results of a life-cycle assessment (LCA) of selected lead-based and lead-free solder alternatives. The structure of the report follows the formal components of a LCA: goal definition and scope are the subject of Chapter 1, inventory analysis is the subject of Chapter 2, and impact assessment is the subject of Chapter 3. The LCA's fourth component, improvement assessment (or interpretation of results), is not directly addressed in this report, but remains for the project partners who review the report.

This chapter provides an overview of the project that is the basis for this report. It includes background information, the project's goals and scope, a summary of the methodology employed in this LCA of lead-based and lead-free solder alternatives, descriptions of the product systems analyzed, and an explanation of parameters that determine the project boundaries.

1.2 PROJECT BACKGROUND

The Lead-Free Solder Project (LFSP) is a voluntary, cooperative project among partners that include the Design for the Environment (DfE) Program of the U.S. Environmental Protection Agency's (EPA) Office of Pollution Prevention and Toxics, the Electronic Industries Alliance (EIA), the IPC–Association Connecting Electronics Industries (IPC), individual electronics industry companies, a high-technology research group (International Sematech), and the University of Tennessee (UT) Center for Clean Products and Clean Technologies. The purpose of the LFSP is to objectively assess the environmental life-cycle impacts of selected lead-free solders as substitutes for lead-based solder. Aside from offering a baseline life-cycle assessment of lead-based and lead-free solders, the DfE LFSP analysis also provides an assessment of the recyclability and leachability of both types of solder.

EPA's Office of Pollution Prevention and Toxics established the DfE Program in 1992 to encourage businesses to incorporate environmental concerns into their business decisions. The EPA DfE Program promotes risk reduction, pollution prevention, energy efficiency, and other resource conservation measures through process choices at a facility level. DfE industry projects are cooperative, joint efforts among trade associations, businesses, public interest groups, and academia to assist specific industries in identifying and evaluating environmentally sound products, processes, and technologies. The DfE LFSP partnership consists of solder manufacturers, manufacturers that use solder in their products, original equipment manufacturers (OEMs) that incorporate components containing solder into their products, industry trade association members, academic institutions, public interest groups, and EPA. The direction and focus of the LFSP was determined by the project partners.

The DfE LFSP used LCA as a tool to evaluate the environmental effects of lead-based and lead-free solders. A LCA is a comprehensive method for evaluating the full life cycle of the product system, from materials acquisition through manufacturing to use and final disposition. There are four major components of a LCA study: (1) goal definition and scope, (2) life-cycle inventory (LCI), (3) life-cycle impact assessment (LCIA), and (4) interpretation of results (also called improvement assessment). LCAs are generally global in scope and non-site-specific. The LFSP study incorporates goal definition and scoping as it is recommended in the LCA process (e.g., Curran, 1996; Fava *et al.*, 1991; ISO, 1996).

1.3 GOALS AND SCOPE: WHY PERFORM A LIFE-CYCLE ASSESSMENT OF SOLDERS?

Defining goals and scope, the first phase of any LCA, is crucial to the project's success because it determines why the LCA is being conducted and its general intent, as well as specifying the product systems and data categories to be studied. These are addressed in the sections below, which describe the project's purpose, prior research, the need for the LFSP, market trends, and its target audience. A description of the LCA methodology specific to this project follows in Section 1.4, and descriptions of the product systems assessed and assessment boundaries used in the LCA can be found in Sections 1.5 and 1.6.

1.3.1 Lead-Free Solder Project Purpose

The purpose of the LFSP study is three-fold:

(1) to establish an objective, 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 the end-of-life; and
(3) to identify data gaps or other potential areas of analysis for future investigation by EPA or industry.

This study evaluates both lead-based and lead-free solder alternatives, and considers impacts related to material consumption, energy use, air resources, water resources, landfills, human toxicity, and ecological toxicity, as well as leachability and recycling.

1.3.2 Previous Research

Substantial research has been conducted on lead-free solders that focuses on the performance aspects of potential substitute alloys, including research by the National Center for Manufacturing Sciences (NCMS), National Electronics Manufacturing Initiative (NEMI), and Interconnect Technology Research Institute (ITRI). A number of these research efforts, along with their findings, have been summarized in a separate DfE project report entitled *Summary of Lead-Free Solder Performance Based on Existing Data Provided by the Electronics Industry* (EPA, 2002). A summary of which is included in Appendix F.

In addition, some work on the health and environmental impacts of lead-free solder alternatives has been conducted or is on-going in other countries and by individual companies. The European Union has focused its research on the risks associated with lead solder, while a multi-national, Japanese-based "Next Generation of Environmentally Friendly Soldering Technology" (EFSOT) project is addressing, among other things, the life-cycle impacts of products using lead-free solders. The multi-national research effort should be completed in 2005.

There also have been a couple of screening-level LCAs that evaluated select lead-free solders over a limited scope, primarily using pre-existing data or focusing on select life-cycle stages (Warburg, 2003; Van der Wel, 2002). A quantitative LCA addressing both lead-based and the lead-free solder alternatives like those selected for this study has not been completed, however, nor has there been adequate evaluation of the leachability and recyclability of lead-free solder alternatives.

1.3.3 Need for the Project

Lead is a key ingredient in electronic products. Releases of lead into the ambient or workplace environment may occur from the mining or processing of lead or from the recycling or disposing of products containing lead. Lead is a heavy metal that has been linked to developmental abnormalities in fetuses and in children who ingest or absorb lead. Small amounts of lead may cause hypertension and permanent mental dysfunction in adults. The Department of Health and Human Services (DHHS) has determined that, based on animal studies, lead acetate and lead phosphate may reasonably be anticipated to be carcinogens. Further, lead is a toxic chemical that persists and bioaccumulates in the environment (DHHS, 1999). The toxic nature of lead has resulted in global efforts to reduce its use.

Concern over lead's toxic effects and ensuing market and regulatory pressures have led the U.S. electronics industry to commit to adopting lead-free solders. Such a commitment requires that industry know as soon as possible which solder alternatives present the fewest potential risks to both the environment and public health. Many other organizations and individuals in the United States and abroad have expressed interest in obtaining objective, detailed information about the life-cycle impacts of lead-free solders.

Various compositions of alloys containing tin, silver, copper, bismuth, and antimony have been identified as leading candidates for solder substitutes. The performance of the metals and fluxes of many of the alternatives has been studied, but their toxicity and environmental impacts have not yet been evaluated. It is crucial to identify the potential impacts of the most promising solder alternatives in order to determine whether any of the lead-free solders may present significant health or environmental impacts or if previously unrecognized consequences may arise from their use. In addition to the question of impacts, issues such as the availability of certain metals and potential differences in workplace exposures need to be addressed. The use of lead-free solder alternatives is a significant technological change. The electronics industry would like to be confident that the choices made over the next few years will not be found later to pose significant, unexpected risks.

Switching to lead-free solder will require substantial capital expenditures and could have a broad impact on public health and the environment. Managing the environmental impacts posed by this change is crucial to the long-term environmental sustainability of both the U.S. and global economies. As a result, the electronics industry, public-interest groups, and governmental organizations are all concerned about assessing the environmental and human-health impacts of the lead-free alternatives to lead-based solder.

Given the current trends toward lead-free solders, the environmental concerns about lead-based solder, and the fact that the relative environmental impacts of solder alternatives have not yet been completed, this study fills a need for a quantitative environmental life-cycle analysis of lead-free solders. The LFSP offers the opportunity to mitigate current and future risks by assisting the electronics industry to identify lead-free solders that are less toxic and that pose the fewest risks over their life cycle. In addition, when this study began, only limited information on leachability and recycling was available for some of the alternatives; this report addresses both of these issues.

1.3.4 Market Trends

In the year 2000, approximately 48,000 tons (97 million pounds) of lead-based solder were used worldwide (Bernier, 2002). Initiatives in Europe and Japan mandate or require voluntary elimination of lead from electronic products. In Europe, the Restriction of Hazardous Substances (ROHS) in Electrical and Electronic Equipment (2002/95/EC) stipulates restrictions on the use of hazardous substances and will require lead and other selected toxic chemicals in electrical and electronic equipment to be replaced by July, 2006. 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 end-of-life (EOL) product recycling.

Electronics in the United States is a $400 billion-per-year industry facing significant legislative and market pressures to phase out the use of lead-based solder and switch to lead-free alternatives (CEA, 2003). Consumer demand for lead-free products also may increase as the general public becomes more aware of lead issues, for example, as a result of EPA's successful efforts to eliminate lead in gasoline, paint, and dust/soil. All these forces combine to drive the U.S. electronics market inexorably toward lead-free solders.

1.3.5 Target 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 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. This 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 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. In addition, 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 impacts to public health and the environment over their entire life cycles. The study results also should help governmental organizations to better manage their electronics purchasing and EOL disposition activities, and to inform the activities of community action groups.

1.4 SUMMARY OF LIFE-CYCLE ASSESSMENT METHODOLOGY

As defined by the Society of Environmental Toxicology and Chemistry (SETAC), the four major components of an LCA are:

(1) goal definition and scoping;
(2) inventory analysis;
(3) impact assessment; and
(4) improvement assessment.

More recently, ISO 14040: Environmental Management—Lifecycle Assessment—Principles and Framework, has defined the four major components of an LCA as:

(1) goal and scope;
(2) inventory analysis;
(3) impact assessment; and
(4) interpretation of results.

The SETAC and International Standards Organization (ISO) LCA frameworks are essentially synonymous with respect to the first three components, but differ somewhat with respect to the fourth component, “improvement assessment” vs. “interpretation of results.” “Improvement assessment” is the systematic evaluation of opportunities for reducing the environmental impacts of a product, process, or activity. “Interpretation of results” is the phase of an LCA in which the findings from the inventory analysis and the impact assessment are combined together, consistent with the defined goal and scope, in order to reach conclusions and recommendations. Under either definition, this fourth component of the LFSP LCA remains for the project partners and is not addressed in this report. The first three components of the LCA (which are essentially the same for both the SETAC and ISO standards) for lead-based and lead-free solders are detailed in separate chapters of this report.

The goals and scope of the lead-based and lead-free solder LCA, introduced in Section 1.3, are the overall subject of Chapter 1 of the report. The second component, inventory analysis, involves the quantification of raw material and fuel inputs, and solid, liquid, and gaseous emissions and effluents. The approach to the LCI in this study involved defining product materials (e.g., solders), developing a bill of materials (BOM) of the products, and collecting inventory data for each process within each life-cycle stage. Details of the LCI data-gathering activities are provided in Chapter 2.

The third component of the LCA, LCIA, involves the translation of the environmental burdens identified in the LCI into environmental impacts. LCIA is typically a quantitative process involving characterization of burdens and assessment of their effects on human and ecological health, as well as other effects such as smog formation and global warming. This project uses an LCIA methodology that incorporates more detailed health effects compared to many other typical LCIA methods, to more fully reflect the concerns of policy makers, public interest groups, and the electronics industry. Details of the LCIA methodology are presented in Chapter 3.

From a general perspective, LCA evaluates the life-cycle environmental impacts from each of the following major life-cycle stages:

- raw materials extraction/acquisition;
- materials processing;
- product manufacture;
- product use; and
- final disposition/end-of-life.

Figure 1-1 briefly describes each of these stages for a solder product system. The resource flows (e.g., materials and energy inputs) and the emissions, waste, and product flows (e.g., outputs) within each life-cycle stage, as well as the interaction between each stage (e.g., transportation) are evaluated to determine the environmental impacts.

RAW MATERIALS EXTRACTION/ACQUISITION (UPSTREAM)
Activities related to the acquisition of natural resources, including mining non-renewable material, harvesting biomass, and transporting raw materials to processing facilities.

MATERIALS PROCESSING (UPSTREAM)
Processing natural resources by reaction, separation, purification, and alteration steps in preparation for the manufacturing stage; and transporting processed materials to product manufacturing facilities.

PRODUCT MANUFACTURE
Processing materials into solder and solder alternatives.

USE/APPLICATION
Application of the solders as the solders are used in manufacturing various products (e.g., printed wiring board and component manufacturing processes).

END-OF-LIFE
At the end of its useful life, the solders, which are part of another product, as produced in the use stage, are retired. If reuse and recycle of the solder is feasible, the product can be transported to an appropriate facility and disassembled or demanufactured for materials recovery. Materials that are not recoverable are then transported to appropriate facilities and treated (if required or necessary) and/or disposed of.

Figure 1-1. Life-Cycle Stages of Solder Alternatives

1.5 PRODUCT SYSTEMS

The following sections describe the product systems that are the subject of the LFSP LCA and how the solder alternatives are compared for the purposes of the study.

1.5.1 Solder Alternatives

The solders investigated in this study are listed in Table 1-1. Solders were selected for evaluation by the project participants based on such factors as current trends and performance studies (see Section 1.3.2). Tin-lead (SnPb) solder was selected as the baseline solder for the evaluation. Tin-copper (SnCu) was selected because it is currently being used by segments of the industry as a low-cost substitute for SnPb in wave solder applications. Tin-silver-copper (SAC) was selected because of its ability to function in both a bar solder and paste environment, and because it appears—through testing— to be emerging as a top choice for a possible substitute for SnPb (NEMI, 2002). Finally, the evaluation group includes two bismuth-containing solders to assess their environmental impacts, particularly at the EOL, because they are currently being considered by several project partners as viable replacements for lead-based solder.

The solders selected represent both paste and bar solders. Paste solders are used for attaching surface mount components to the surface of printed wiring boards (PWBs). In general, where circuitry is sufficiently complex or the size of the assembly is an important design criteria, most high-end applications and much of the consumer market electronics require assembly with paste solders. Conversely, low-complexity electronics applications (e.g., many toys) often use single-sided or double-sided PWBs and lower cost through-hole components. These lower-end, low-cost applications are often assembled using bar solders, which are simpler to apply and less costly to produce.

Table 1-1. Solders selected for evaluation

Solder alloys	Composition	Density (g/cc)	Melting Point (ºc)	Solder 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

Ag=Silver; Bi=Bismuth; Cu=Copper; Pb=Lead; Sn=Tin

1.5.2 Functional Unit

The product systems being evaluated in this project are either lead-based or lead-free solders currently in use within the electronics industry. In an LCA, product systems are evaluated on a functionally equivalent basis. The functional unit normalizes data based on equivalent use 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 (Figure 1-2). The functional unit is based on the understanding that a similar volume of solder is required to fill the space in a solder joint regardless of the type of solder used. The selection of this functional unit is independent of PWB design or configuration, since the number and types of connections formed by the solder would be the same for each alternative. As a result, a volume of one thousand cubic centimeters (cc) of solder was selected for use as the functional unit in the LCA.

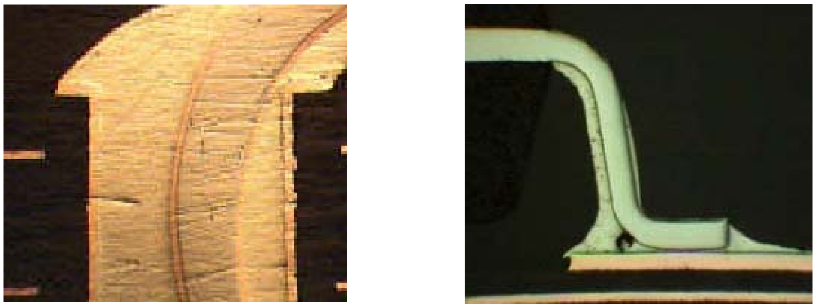


Figure 1-2. Typical Solder Joints for Both Through-hole and Surface Mount Connections

1.6 ASSESSMENT BOUNDARIES

The following sections explain more about the data categories, the physical and geographic limitations, and general exclusions to the LFSP LCA, all of which combine to determine the project boundaries.

1.6.1 Life-Cycle Stages and Unit Processes

As noted above, in a comprehensive cradle-to-grave analysis such as this LCA, the product system includes five life-cycle stages:

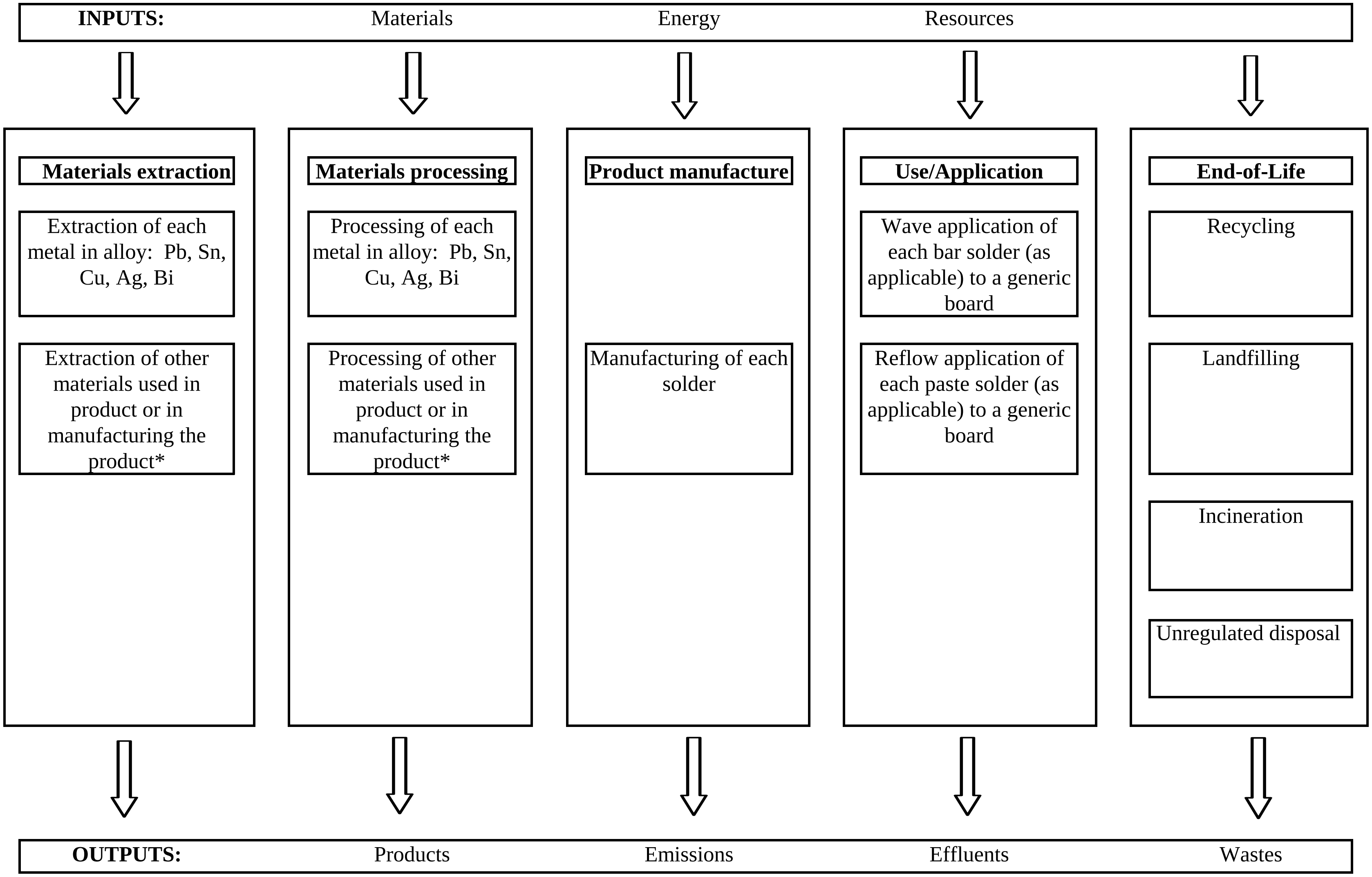
(1) raw materials acquisition;
(2) materials processing;
(3) product manufacture;
(4) product use/application; and
(5) final disposition/EOL.

Also included are the activities that are required to affect movement between the stages (e.g., transportation). The major processes within the life cycles of the solders that were modeled in this study are depicted in Figure 1-3. Each process box represents a unit process that has its own inventory of inputs and outputs.

Because of process differences during the product use/application stage between paste and bar solders, the two groups of solders could not be evaluated together within a single LCA. As such, separate LCAs were conducted comparing each group of solders identified in Table 1-1. LCA results for both paste and bar solder are presented separately within each section of this report.

1.6.2 Spatial and Temporal Boundaries

Geographic boundaries are used in a LCA to show where impacts are likely to occur for each life-cycle stage. This is important for assessing the impact of such activities as transportation of materials between life-cycle stages. For example, acquisition and processing of materials used in the manufacture of the metals comprising the solder alloys is done throughout the world and is represented by a worldwide database. Product manufacturing also occurs worldwide with data being collected from U.S. and Japanese sources. Similarly, solder application in the use stage is done worldwide; however, 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.



* Additional materials will be included if they meet project decision rules.

Figure 1-3. Solder Life-Cycle Conceptual Model

1.6.3 General Exclusions

A number of items have been excluded from the LCA. General exclusions of processes or data are as follows:

- impacts associated with the infrastructure needed to support manufacturing facilities (e.g., general plant maintenance);
- use of the final product in which a PWB is installed where no flows of or exposure to solder metals are likely to occur (e.g., use of a personal computer; however, energy and solder flows from EOL recycling or disposal of that final product is included in the LCA's scope);
- lead or other solder metals used in non-solder parts of a PWB (e.g., on the surface finish); and
- transportation between life-cycle stages (due to the large diversity of materials sources and intended markets).

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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.

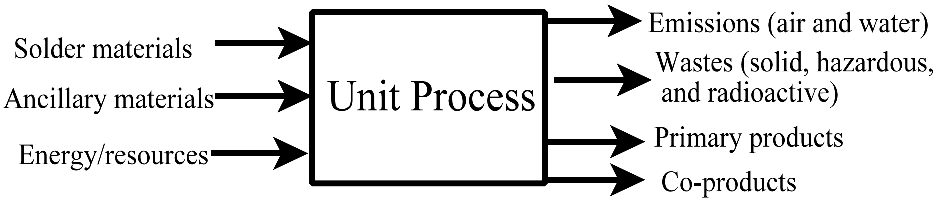
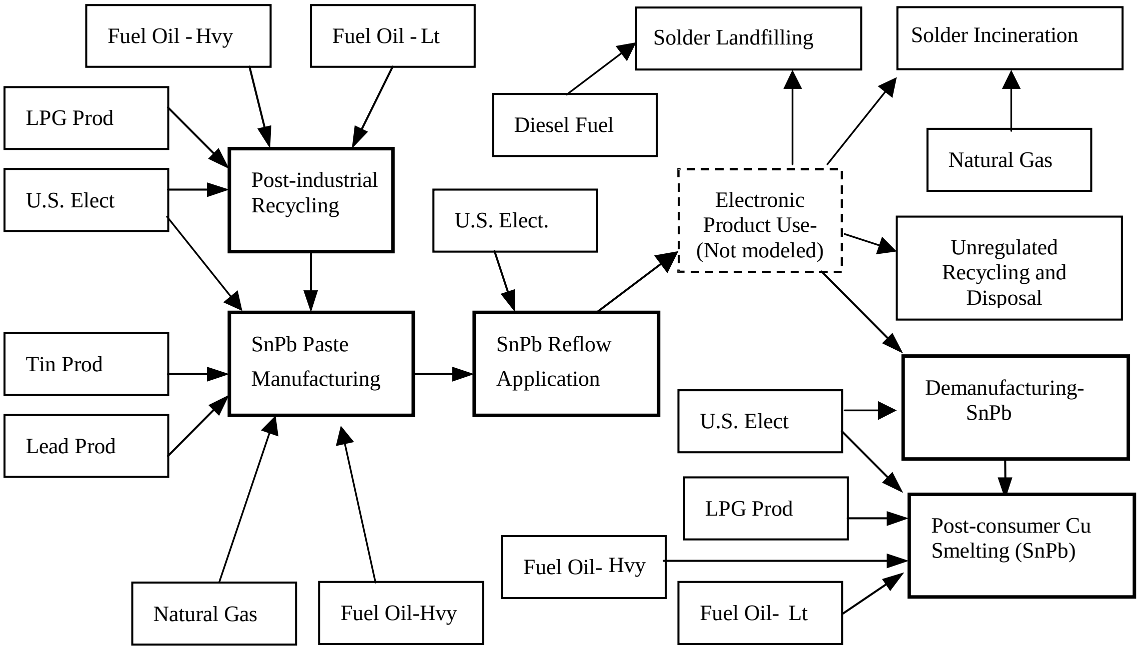


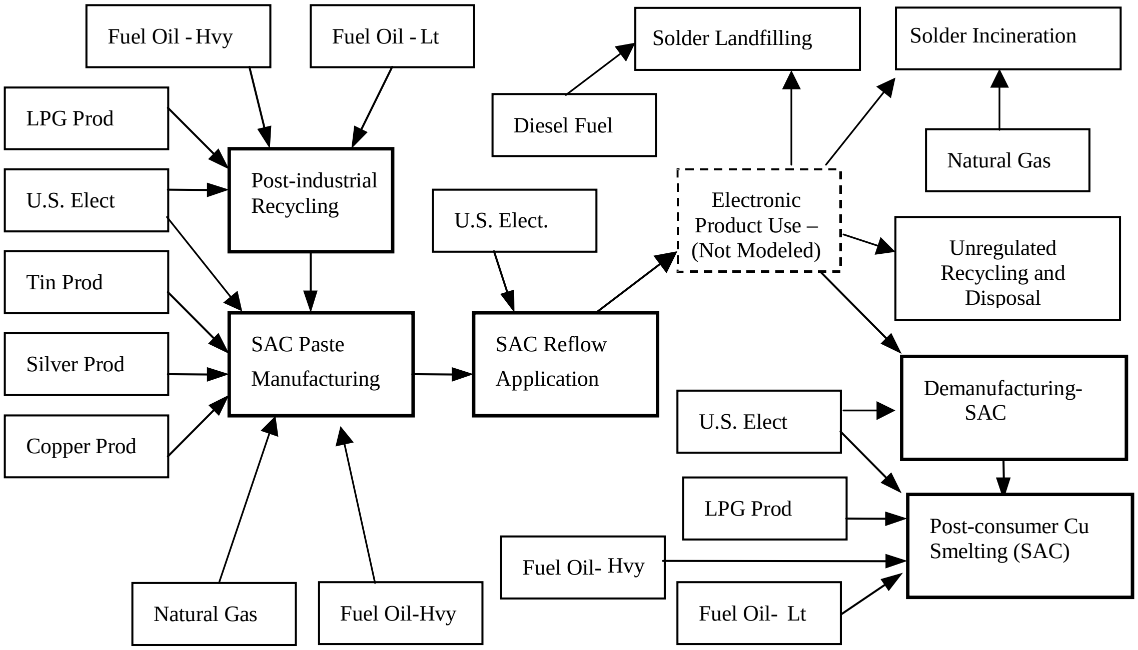
Figure 2-1. Unit process inventory conceptual diagram

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.



Bold= Primary Data
Dash= Not modeled

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



Bold= Primary Data
Dash= Not modeled

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

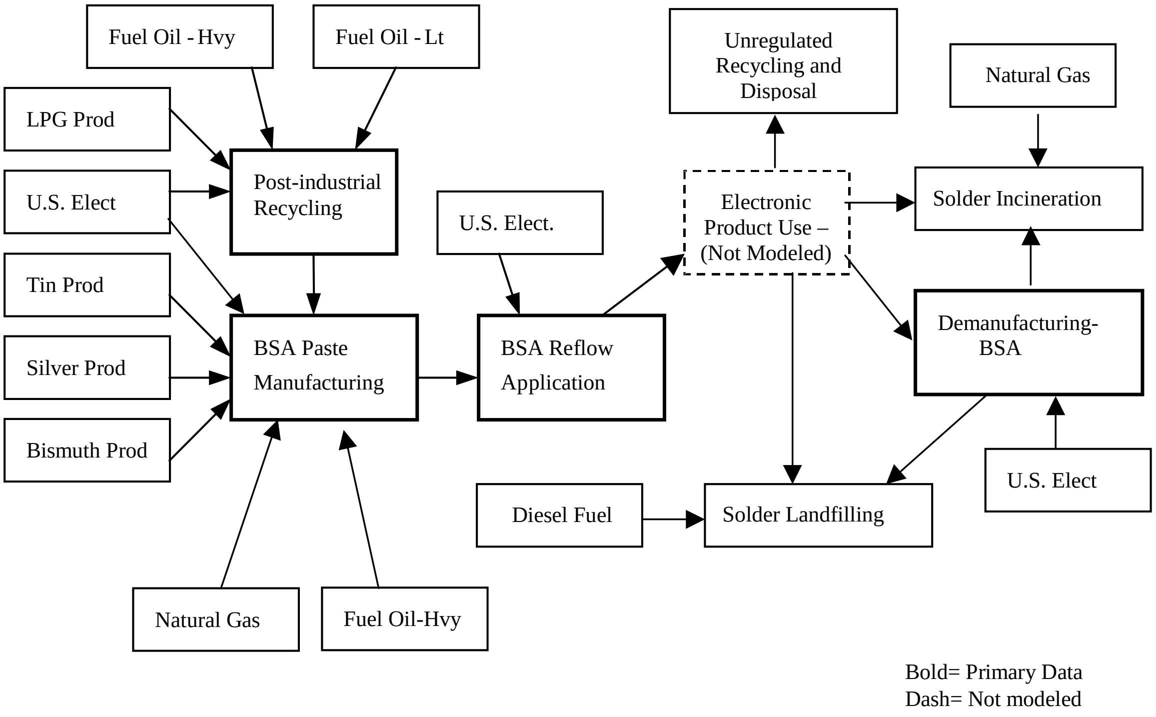


Figure 2-4. BSA Paste Solder Life-Cycle Processes

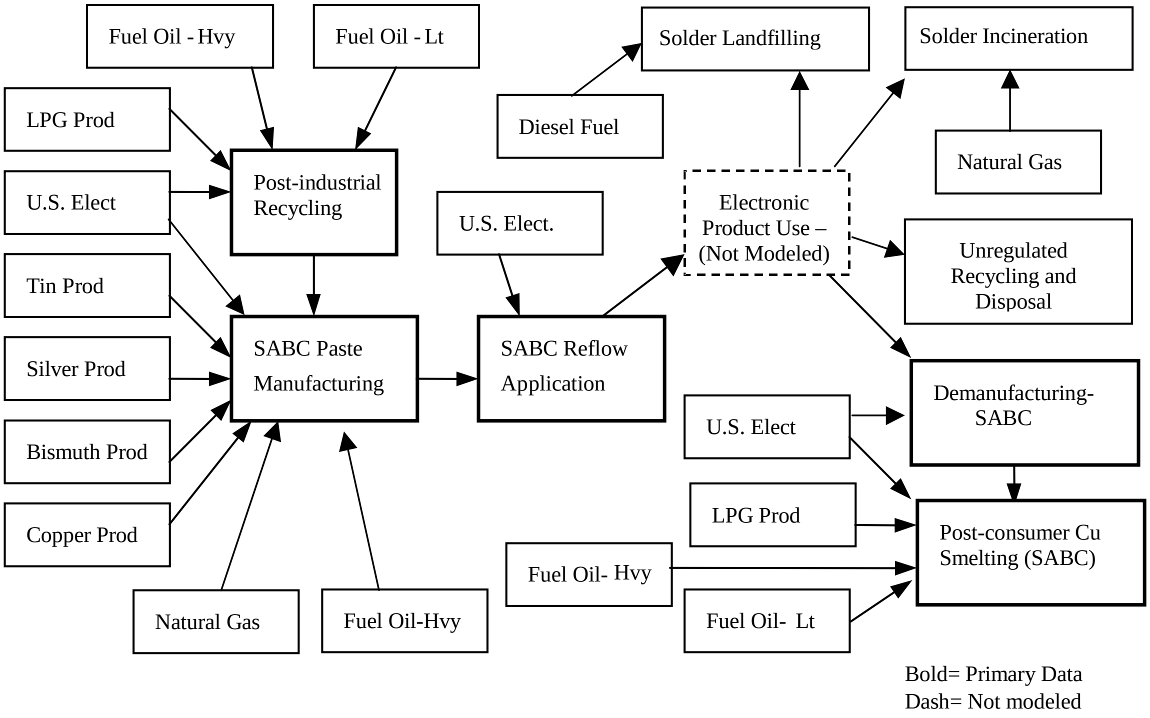


Figure 2-5. SABC Paste Solder Life-Cycle Processes

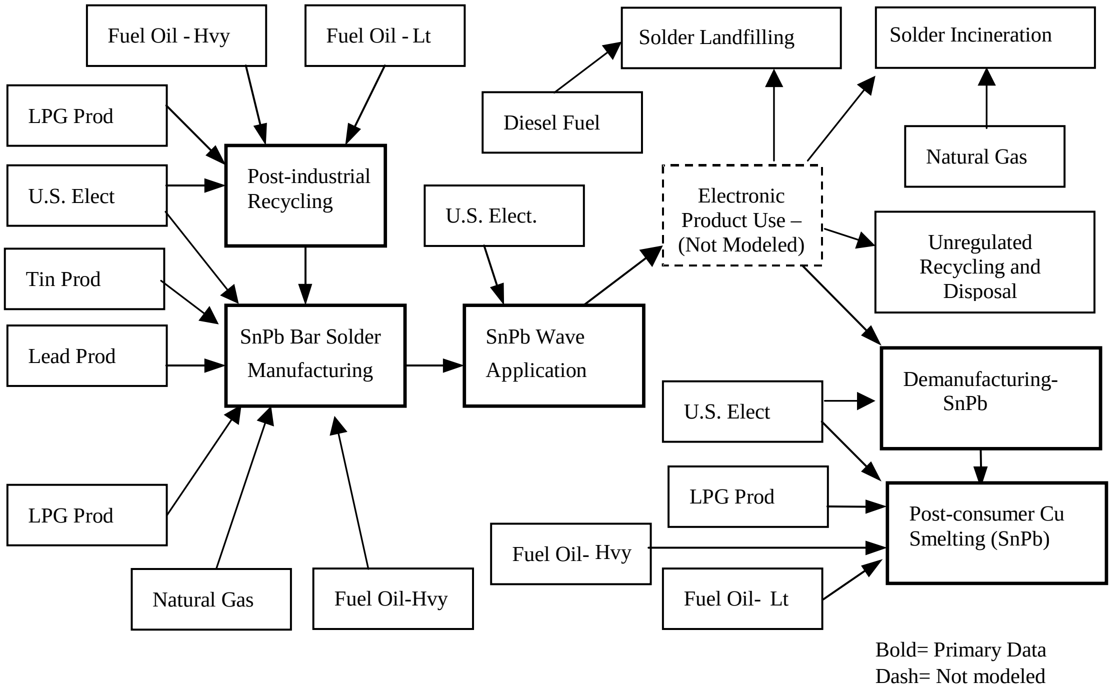


Figure 2-6. SnPb Bar Solder Life-Cycle Processes

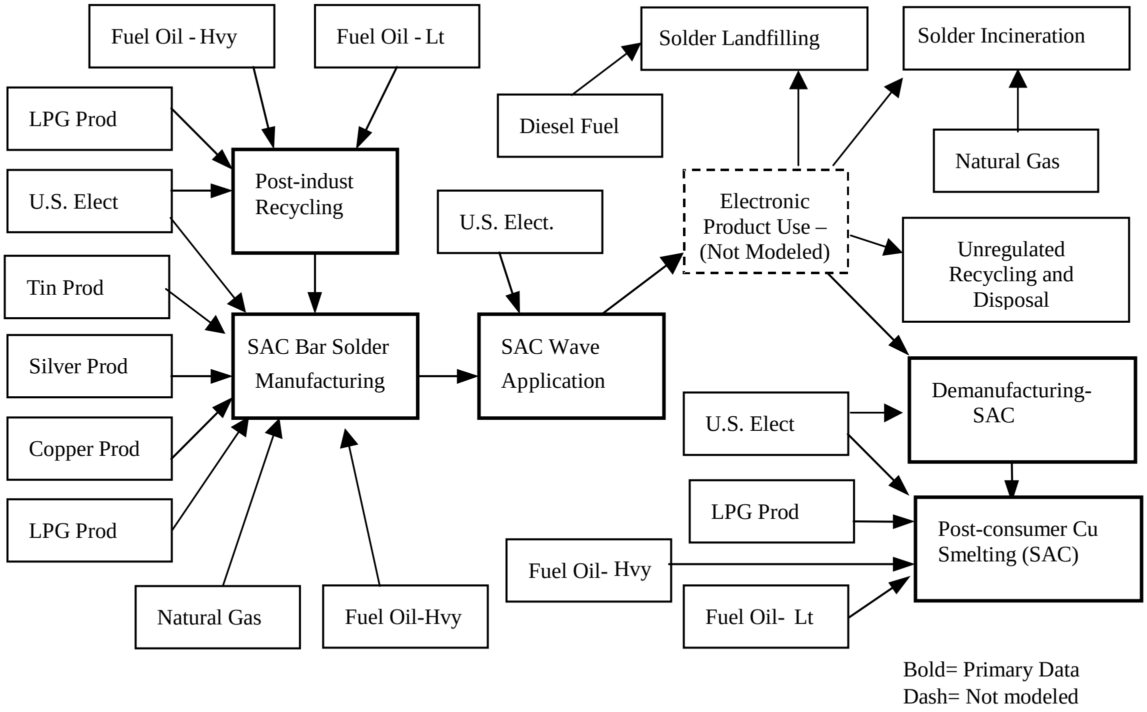


Figure 2-7. SAC Bar Solder Life-Cycle Processes

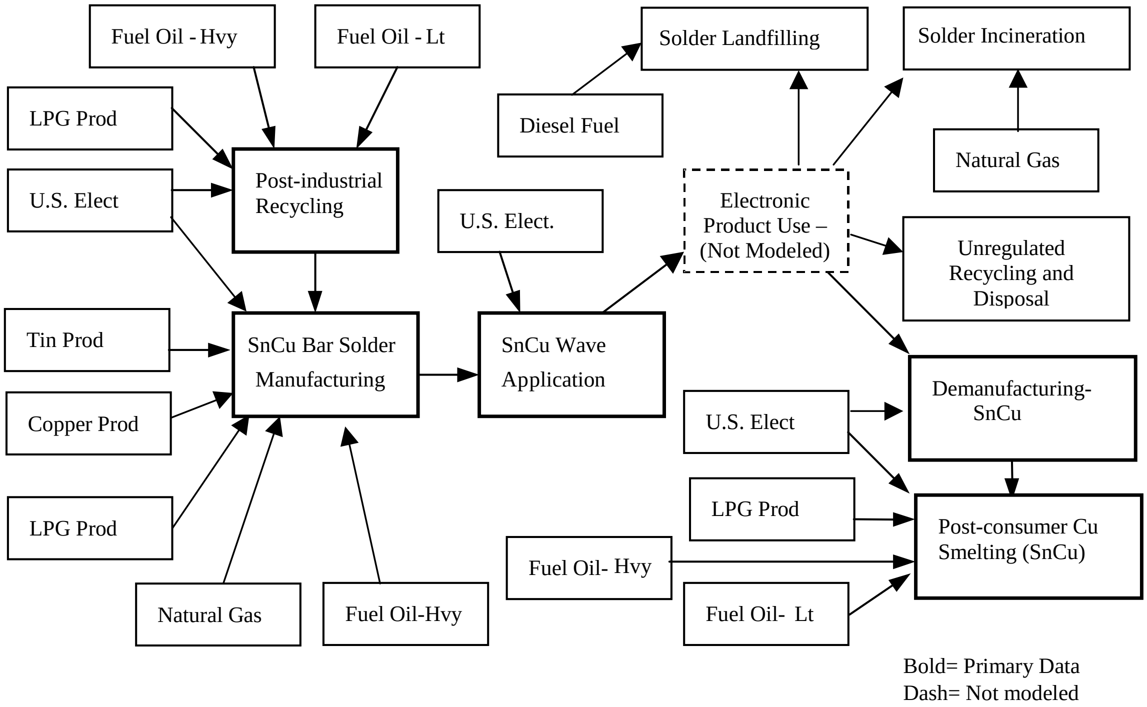


Figure 2-8. SnCu Bar Solder Life-Cycle Processes

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 (materials extraction and processing)	Secondary data	Less emphasis
Product manufacturing	Primary data	Greater emphasis
Use (solder application)	Primary data	Greater emphasis
Final disposition (leachability, recycling, and/or disposal)	Primary and secondary data. 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.

- *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.

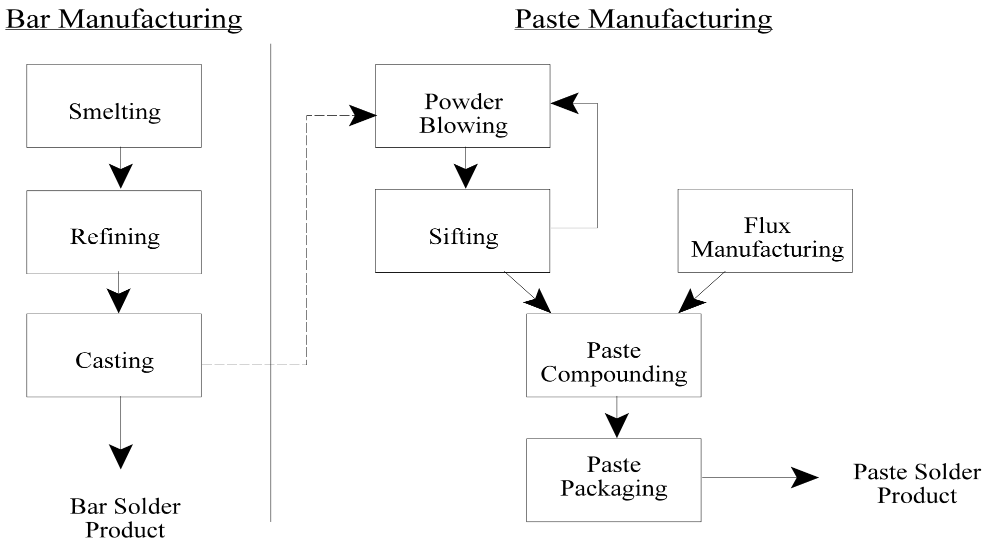

Figure 2-9. Solder Manufacturing Process Diagrams for Bar and Paste Solders

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.

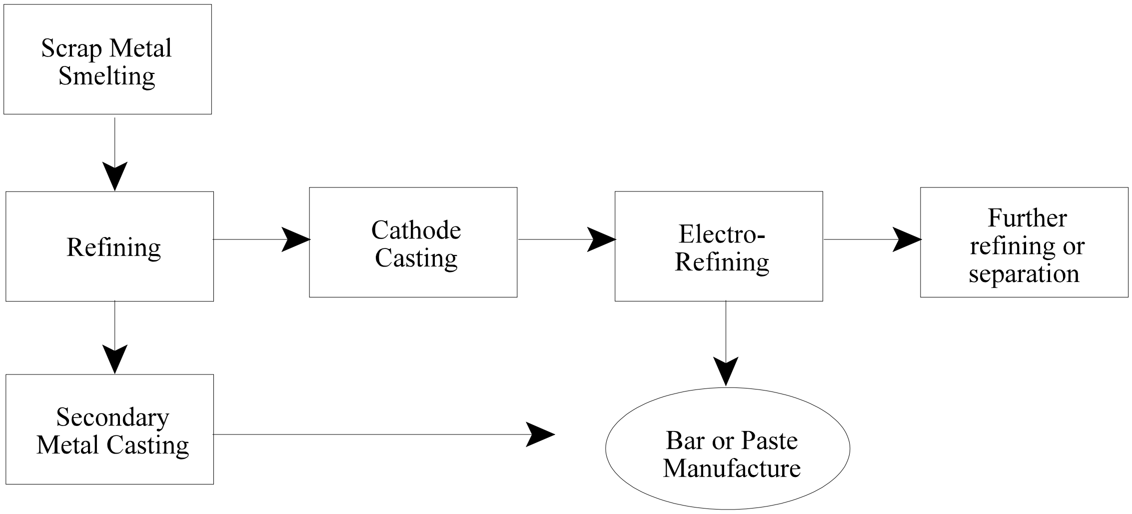

Figure 2-10 Typical Post-Industrial Recycling Process Flow Diagram

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.

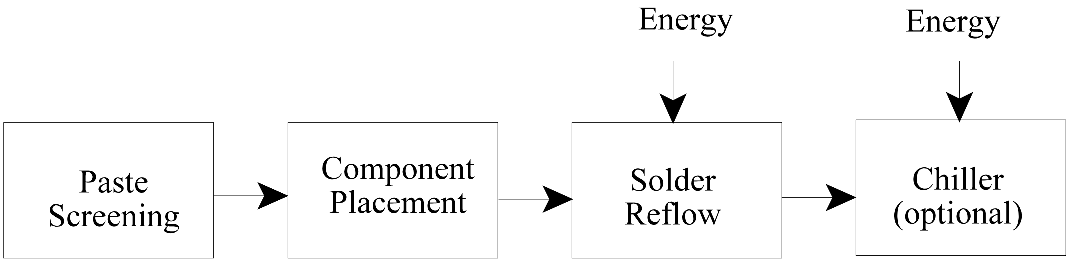

Figure 2-11. Solder Paste Reflow Process Diagram

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.

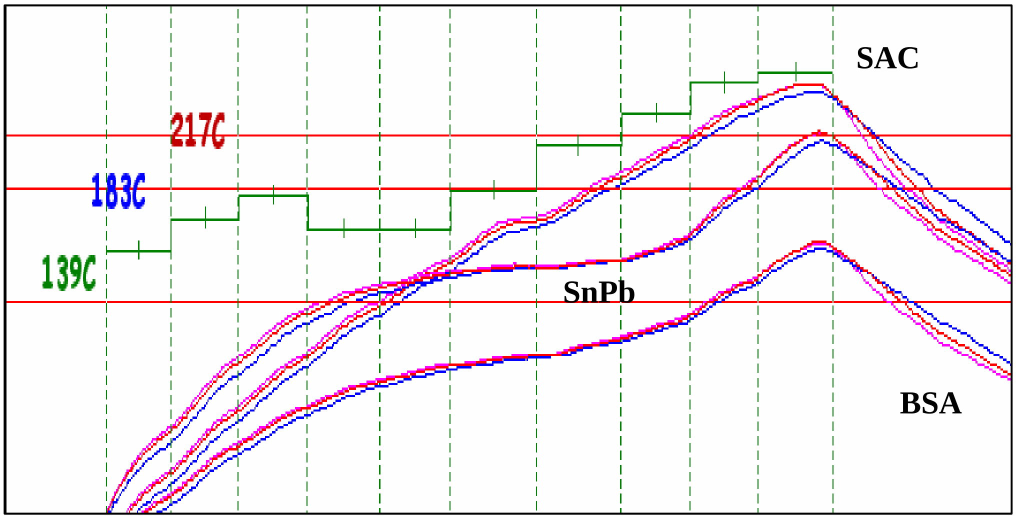

Figure 2-12. Reflow Profiles for Solder Pastes

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.

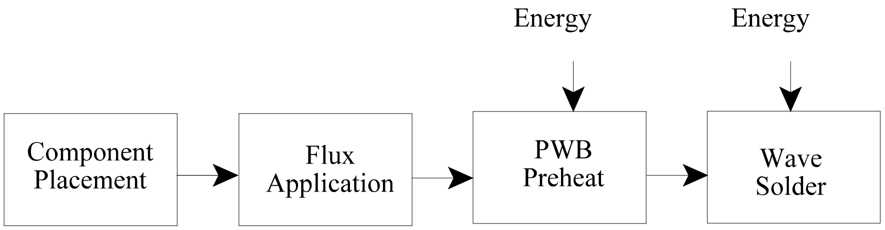

Figure 2-14. Process Flow Diagram for Wave Solder

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 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.

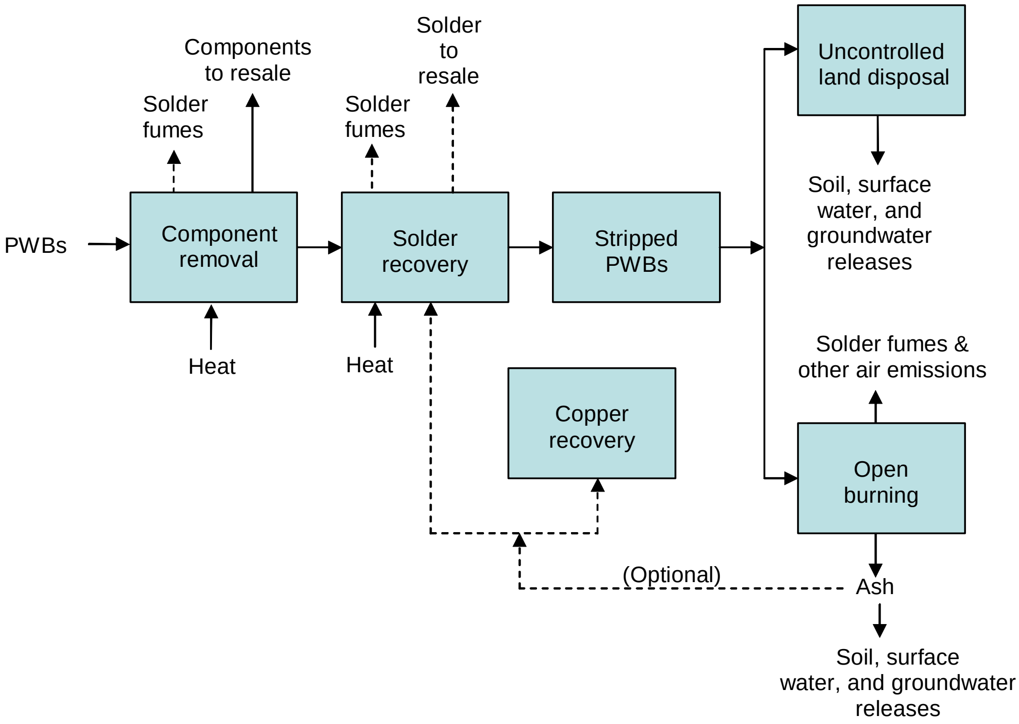

Figure 2-15. Unregulated Recycling and Disposal Process Flow Diagram

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.

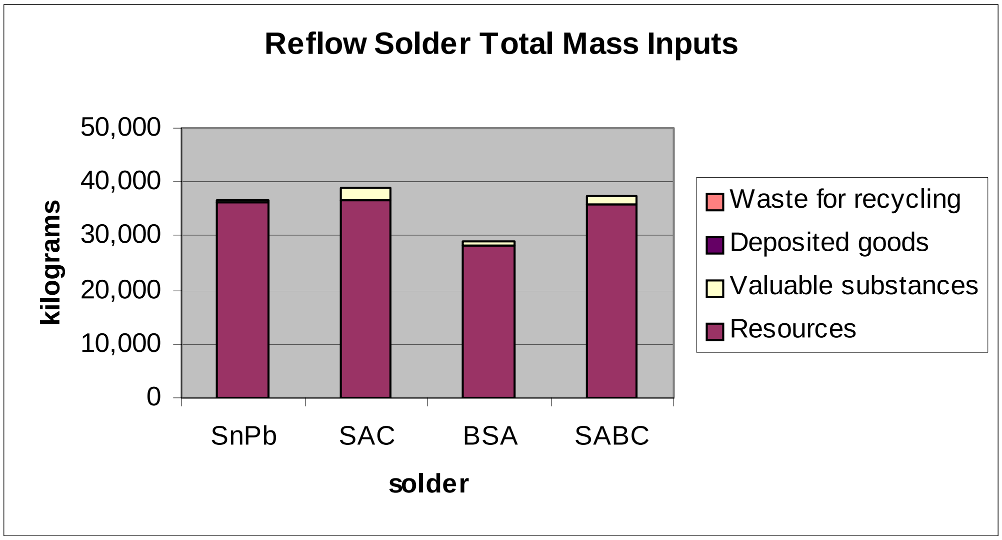

Figure 2-16. Paste Solder Total Mass Inputs

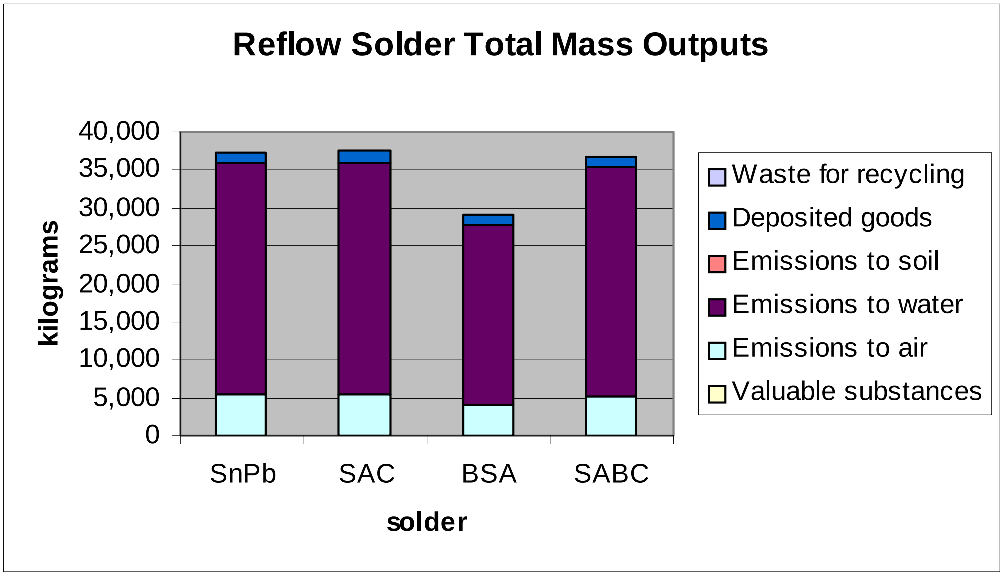

Figure 2-17. Paste Solder Total Mass Outputs

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.

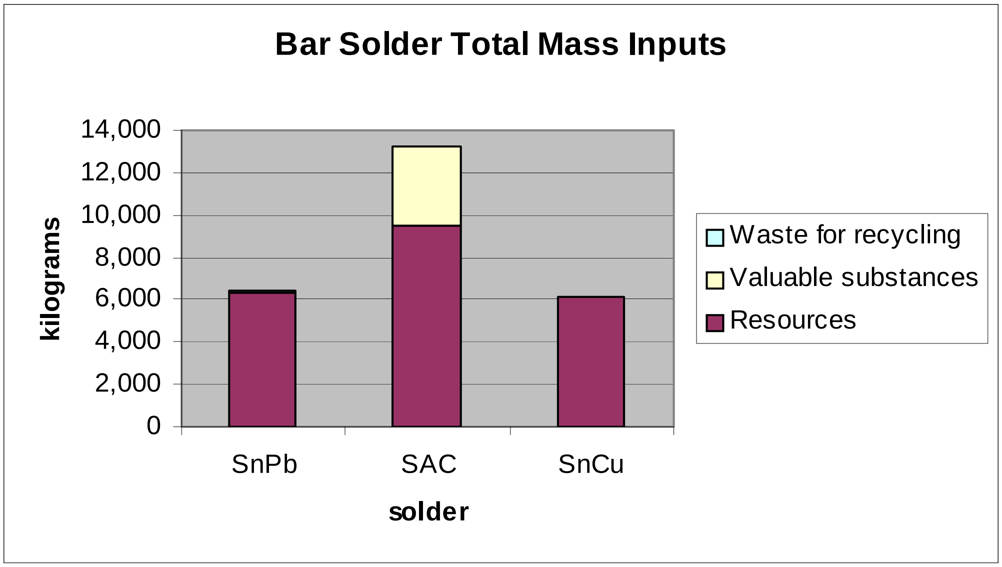

Figure 2-18. Bar Solder Total Mass Inputs

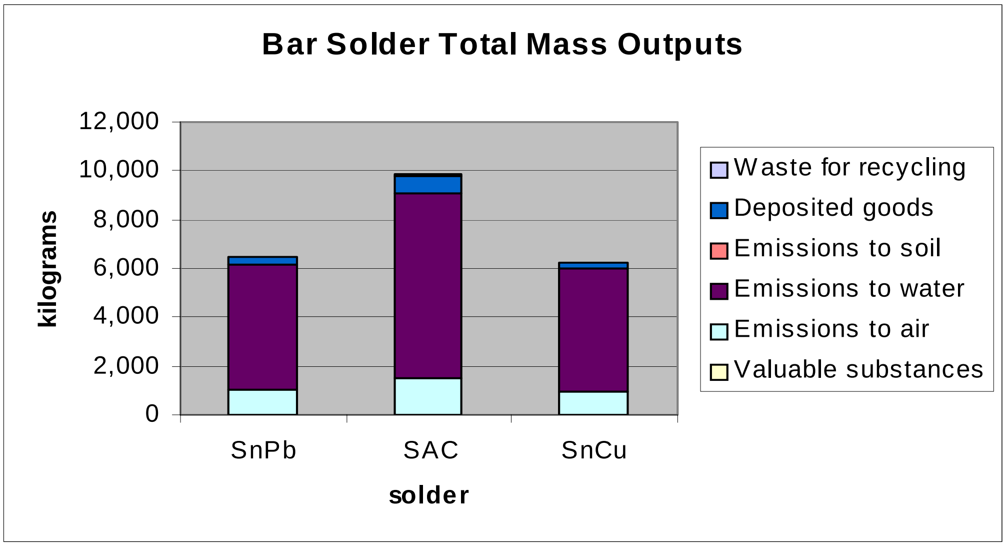

Figure 2-19. Bar Solder Total Mass Outputs

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Chapter 3

LIFE-CYCLE IMPACT ASSESSMENT

Within LCA, the LCI is a well-established methodology; however, LCIA methods are less well-defined and continue to evolve (Barnthouse *et al.*, 1997; Fava *et al.*, 1993). For LCIA toxicity impacts in particular, some of the methods commonly being applied include toxicity potential, critical volume, and direct valuation (Guinee *et al.*, 1996; ILSI, 1996; Curran, 1996). There is currently no general consensus among the LCA community concerning which, if any, of these methods are preferable, however. Efforts are under way to determine the appropriate level of analytical sophistication in LCIA for various types of decision-making requirements and for adequately addressing toxicity impacts (Bare, 1999).

Section 3.1 of this chapter presents the general LCIA methodology used in this LFSP study, which takes a more detailed approach to chemical toxicity impacts than some of the methods currently being used. This section also describes the data management and analysis software used to calculate LCIA results. Section 3.2 presents the detailed characterization methodologies for each impact category as well as the baseline LCIA results from the paste and bar analyses. This section also discusses data sources, data quality, and the limitations and uncertainties in this LCIA methodology as well as in the LCIA results. Section 3.3 presents alternative analyses of the baseline results.

Our LCIA methodology calculates life-cycle impact category indicators using established calculation methods for a number of traditional impact categories, such as global warming, stratospheric ozone depletion, photochemical smog, and energy consumption. In addition, this method calculates relative category indicators for potential impacts on human health and aquatic ecotoxicity, impacts not always considered in traditional LCIA methodology. The toxicity impact method is based on work for Saturn Corporation and the EPA Office of Research and Development by the UT Center for Clean Products and Clean Technologies and used in the DfE Computer Display Project (Socolof *et al.*, 2001).

3.1 METHODOLOGY

In its simplest form, LCIA is the evaluation of potential impacts to any system as a result of some action. LCIAs generally classify the consumption and loading data from the inventory stage to various impact categories. Characterization methods are used to quantify the magnitude of the contribution that loading or consumption could have in producing the associated impact. 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.

Conceptually, there are three major phases of LCIA, as defined by the SETAC (Fava *et al.*, 1993):

- **Classification—**The process of assignment and initial aggregation of data from inventory studies to impact categories (i.e., greenhouse gases or ozone depletion compounds).
- **Characterization**—The analyses and estimation of the magnitude of potential impacts for each impact category, derived through the application of specific impact assessment tools. (In the LFSP, "impact scores" are calculated for inventory items that have been classified into various impact categories and then aggregated into life-cycle impact category indicators.)
- **Valuation**—The assignment of relative values or weights to different impacts, and their integration across impact categories to allow decision makers to assimilate and consider the full range of relevant impact scores across impact categories.

The international standard for life-cycle impact assessment, ISO 14042, considers classification and characterization to be mandatory elements of LCIA; valuation ("weighting") is an optional element to be included depending on the goals and scope of the study. Both the classification and characterization steps are completed in the LFSP, while the valuation step is left to industry or others interested stakeholders. The methodologies for life-cycle impact classification and characterization are described in Sections 3.1.1 and 3.1.2, respectively.

3.1.1 Classification

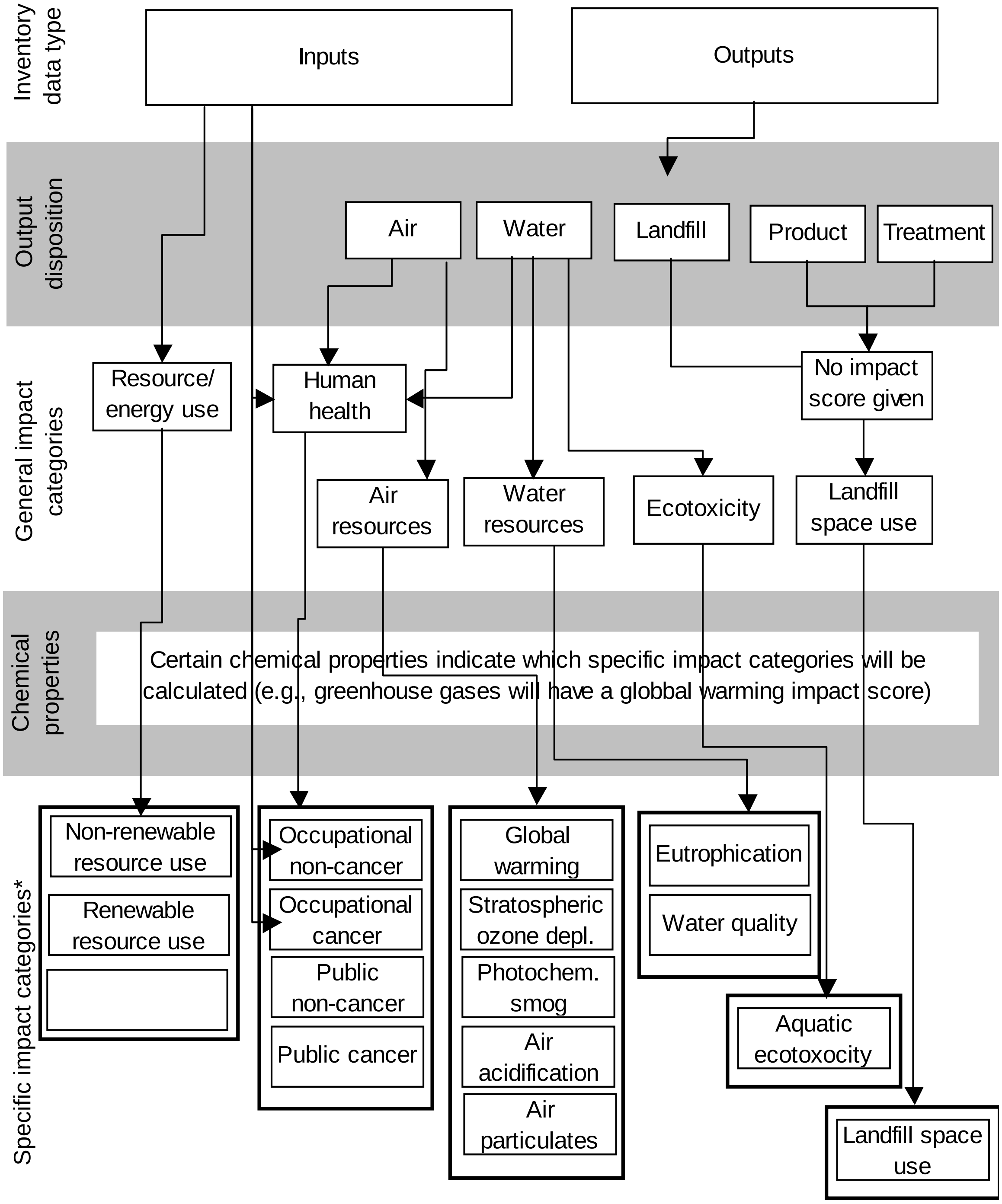
In the first step of classification, impact categories of interest are identified in the scoping phase of the LCA. The categories included in the LFSP LCIA are listed below:

- Natural Resource Impacts
    - renewable resource use
    - non-renewable materials use/depletion
    - energy use
    - solid waste landfill use
    - hazardous waste landfill use
- Abiotic Ecosystem Impacts
    - global warming
    - stratospheric ozone depletion
    - photochemical smog
    - acidification
    - air quality (particulate matter loading)
    - water eutrophication (nutrient enrichment)
    - water quality (biological oxygen demand [BOD] and total suspended solids [TSS]
- Potential Human Health and Ecotoxicity Impacts
    - chronic cancer human health effects—occupational
    - chronic cancer human health effects—public
    - chronic non-cancer human health effects—occupational
    - chronic non-cancer human health effects—public
    - aquatic ecotoxicity

Radioactivity and radioactive landfill waste are not included as impact categories because they are simply proportional to the use of electricity across all alternatives. Terrestrial ecotoxicity is not included as a separate impact category because the method for calculating chronic non-cancer public health impacts would be the same as for terrestrial ecotoxicity.

The second step of classification is assigning inventory flows to applicable impact categories. Classification includes whether the inventory item is an input or output, the disposition of the output, and, in some cases, the material properties for a particular inventory item. Figure 3-1 shows a conceptual model of classification for the LFSP. Table 3-1 presents the inventory types and material properties used to define which impact category will be applicable to an inventory item. One inventory item may have multiple properties and, therefore, would have multiple impacts. For example, methane is a global warming gas and has the potential to create photochemical oxidants (to form smog).

Output inventory items from a process may have such varying dispositions as direct release (to air, water, or land), treatment, or recycle/reuse. 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 are considered inputs to a treatment process and impacts are not calculated until direct releases from that process occur. Similarly, outputs to recycle/reuse are considered inputs to previous processes and impacts are not directly calculated for outputs that go to recycle/reuse. Figure 3-1 graphically depicts the relationships between inventory type, dispositions, and impact categories. Note that a product is also an output of a process; however, product outputs are not used to calculate any impacts. Once impact categories for each inventory item are classified, life-cycle impact category indicators are quantitatively estimated through the characterization step.



*Equations for calculating impact scores for each category are provided in Section 3.2

Figure 3-1. Impact Classification Conceptual Model

Table 3-1. Inventory types and properties for classifying inventory items into impact categories

Inventory type		Chemical/Material properties	Impact category
Input	**Output**		
Natural Resource Impacts			
Material, fuel	—	Non-renewable	Non-renewable resource use/depletion
Material, water	—	Renewable	Renewable resource use
Electricity, fuel	—	Energy	Energy use
—	waste to landfill	Solid, hazardous, and radioactive waste	Landfill space use (volume)
Abiotic Ecosystem Impacts			
—	Air	Global warming gases	Global warming
—	Air	Ozone depleting substances	Stratospheric ozone depletion
—	Air	Substances that can be photochemically oxidized	Photochemical smog
—	Air	Substances that react to form hydrogen ions (H+)	Acidification
—	Air	Air particulates (PM_{10}, TSP) [a]	Air particulates
—	Water	Substances that contain available nitrogen or phosphorus	Water eutrophication (nutrient enrichment)
—	Water	BOD [a] and TSS [a]	Water quality
Human Health and Ecotoxicity			
Material	—	Toxic material (carcinogenic)	Carcinogenic human health effects—occupational
—	Air, soil, water	Toxic material (carcinogenic)	Carcinogenic human health effects—public
Material	—	Toxic material (non-carcinogenic)	Chronic, non-carcinogenic human health effects—occupational
—	Air, soil, water	Toxic material (non-carcinogenic)	Chronic, non-carcinogenic human health effects—public (and terrestrial ecotoxicity)
—	Water	Toxic material	Aquatic ecotoxicity

[a] Acronyms: particulate matter with average aerodynamic diameter less than 10 micrometers (PM_{10}); total suspended particulates (TSP); biological oxygen demand (BOD); total suspended solids (TSS).

3.1.2 Characterization

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.
- **Equivalency**—An impact score is based on the inventory amount weighed by a certain effect, equivalent to a reference chemical.
  - *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).

Table 3-2 lists the characterization approach used with each impact category. The **loading** approach either uses the direct inventory amount to represent the impact or slightly modifies the inventory amount to change the units into a meaningful loading estimate, such as characterizing the impact of either non-renewable resource depletion or landfill use. Use of nonrenewable resources is directly estimated as the mass loading (input amount) of that material consumed; use of landfill space applies the mass loading (output amount) of hazardous, non-hazardous, or radioactive waste, and converts that loading into a volume to estimate the landfill space consumed.

The **equivalency** method uses equivalency factors in certain impact categories to convert inventory amounts to common units relative to a reference chemical. Equivalency factors are values that provide a measure (weighting) to relate the impact of an inventory amount of a given chemical to the effect of the same amount of the reference chemical. For example, for the impact category "global warming potential (GWP)," the equivalency factor is an estimate of a chemical's atmospheric lifetime and radiative forcing that may contribute to global climate change compared to the reference chemical carbon dioxide (CO_2); therefore, GWPs are given in units of CO_2 equivalents.

Scoring of inherent properties is applied to impact categories that may have different effects for the same amount of various chemicals, but for which equivalency factors do not exist or are not widely accepted. The scores are meant to normalize the inventory data to provide measures of potential impacts. Scoring methods are employed for the human and ecological toxicity impact categories, based on the Chemical Hazard Evaluation Management Strategies (CHEMS-1) method described by Swanson *et al.* (1997) and presented below. The scoring method provides a relative score, or hazard value, for each potentially toxic material that is then multiplied by the inventory amount to calculate the toxicity impact score.

Using the various approaches, the LFSP LCIA method calculates impact scores for each inventory item for each applicable impact category. These 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. Impact scores are then aggregated within each impact category to calculate the various life-cycle impact category indicators.

Inventory amounts are identified on a functional unit basis and used to calculate impact scores. For each inventory item, an individual score is calculated for each applicable impact category. The detailed characterization equations for each impact category are presented in Sections 3.2.1 through 3.2.13 and summarized in Section 3.4. The equations presented in those subsections calculate impacts for individual inventory items that could later be aggregated as defined by the user. Impact scores represent relative and incremental changes rather than absolute effects or threshold levels.

Table 3-2. LCIA characterization approaches for the LFSP

Impact category	**Characterization approach**
Natural Resource Impacts	
Non-renewable materials use/depletion	Loading
Renewable resource use	Loading
Energy use	Loading
Landfill space use	Loading
Abiotic Ecosystem Impacts	
Global warming	Equivalency (full)
Stratospheric ozone depletion	Equivalency (full)
Photochemical smog	Equivalency (partial)
Acidification	Equivalency (full)
Air particulates	Loading
Water eutrophication (nutrient enrichment)	Equivalency (partial)
Water quality (BOD, TSS)	Loading
Human Health and Ecotoxicity	
Cancer human health effects—occupational	Scoring of inherent properties
Cancer human health effects—public	Scoring of inherent properties
Chronic non-cancer human health effects—occupational	Scoring of inherent properties
Chronic non-cancer human health effects—public	Scoring of inherent properties
Aquatic ecotoxicity	Scoring of inherent properties

3.2 CHARACTERIZATION AND RESULTS

This section presents the impact assessment characterization methods and the impact results by impact category. Within each impact category subsection (3.2.1 through 3.2.13), the characterization equations are presented, followed by both the paste and bar solder results. A discussion of the limitations and uncertainties associated with that impact category concludes each section. The LCIA results are based on the boundaries outlined in Chapter 1 and the inventory described in Chapter 2. Within the results subsections of Sections 3.2.1 through 3.2.13, the impacts are presented by life-cycle stage as well as by process. Individual flows that are the greatest contributors to the life-cycle impacts also are presented. Section 3.4 briefly summarizes the characterization methods and the overall life-cycle impact category indicators for the sixteen impact categories for both the paste and bar alloys. A summary of the limitations and uncertainties also is provided in Section 3.4.

For results presented at the process level, processes that consume energy (e.g., electricity during solder application) are presented together as a process group with the associated processes of electricity generation or fuel production. Table 3-3 lists the processes that are grouped together as presented in Sections 3.2.1 through 3.2.13. Note that the metals extraction and processing (ME&P) processes are not included in this list because they are from secondary data that incorporate electricity generation and fuel production into the individual processes themselves. Thus, the ME&P processes inherently include upstream energy sources.

The associated fuels for each process, as described above, also are depicted in the process flow charts of the solder life-cycles in the figures in Chapter 2. For the upstream metals production processes, fuel or energy production data are embedded in the inventories for those processes. Fuel and energy production are included in the upstream results, but are not shown as separate processes in the life-cycle process models shown in the figures in Chapter 2.

It should be reiterated that the LCIA results presented throughout this section are indicators of the relative potential impacts of SnPb and the lead-free solders in various impact categories and are not a measure of actual or specific impacts. The LCIA is intended to provide a screening level evaluation of impacts and in no way provides absolute values or measures actual effects. Results herein are referred to as impact category indicators (representing the total impact score of an alloy in an impact category), impact results, impact scores, or simply impacts. Each of these terms refers to relative potential impacts and should not be confused with an assessment of actual impacts.

Table 3-3. Process groups

Process group	**Associated processes**	
	Paste solder	**Bar solder**
Solder manufacturing	Paste solder manufacturing Electric power production Natural gas production Heavy fuel oil (#6) production	Bar solder manufacturing Electric power production Natural gas production Heavy fuel oil (#6) production Liquified petroleum gas (LPG) production
Post-industrial recycling	Post-industrial recycling Electric power production Heavy fuel oil (#6) production Light fuel oil (#2) production LPG production	Post-industrial recycling Electric power production Heavy fuel oil (#6) production Light fuel oil (#2) production LPG production
Solder application	Reflow solder application on a PWB Electric power production	Wave solder application on a PWB Electric power production
Landfilling	Landfilling Diesel fuel production	Landfilling Diesel fuel production
Incineration	Incineration Natural gas production	Incineration Natural gas production
Demanufacturing	Demanufacturing Electric power production	Demanufacturing Electric power production
Copper smelting	Copper smelting Electric power production Heavy fuel oil (#6) production Light fuel oil (#2) production LPG production	Copper smelting Electric power production Heavy fuel oil (#6) production Light fuel oil (#2) production LPG production

3.2.1 Resource Use (Non-renewable and Renewable)

3.2.1.1 Characterization

Natural resources are materials that are found in nature in their basic form rather than being manufactured. Non-renewable ("stock") natural resources are typically abiotic, such as mineral ore or fossil fuels. Impacts to both of these natural resource types are calculated using the loading approach (described in Section 3.1.2). Renewable ("flow") natural resources are those that can be regenerated, typically biotic resources, such as forest products or other plants, animal products, and water. Consumption impacts from non-renewable resources (NRRs) and renewable resources (RRs) are calculated using direct consumption values (e.g., material mass) from the inventory.

For the non-renewable materials use/depletion category, depletion of materials results from the extraction of non-renewable resources. Non-renewable resource impact scores are based on the amount of material inputs (which can be product or process materials), water, and fuel inputs of non-renewable materials. To calculate the loading-based impact scores, the following equation is used:

$$(IS_{NRR})_i = [Amt_{NRR} \; x \; (1 - RC)]_i$$

where:

IS_{NRR} equals the impact score for use of non-renewable resource *i* (kg) per functional unit;

Amt_{NRR} equals the inventory input amount of non-renewable resource *i* (kg) per functional unit; and

RC equals the fraction recycled content (post-industrial and post-consumer) of resource *i*.

Renewable resource impact scores are based on the following process inputs in the LCI: material inputs (which can be product or process materials), water, and fuel inputs of renewable materials. To calculate the loading-based impact scores, the following equation is used:

$$(IS_{RR})_i = [Amt_{RR} \; x \; (1 - RC)]_i$$

where:

IS_{RR} equals the impact score for use of renewable resource *i* (kg) per functional unit;

Amt_{RR} equals the inventory input amount of renewable resource *i* (kg) per functional unit; and

RC equals the fraction recycled content (post-industrial and post-consumer) of resource *i*.

Depletion of materials, which results from the extraction of renewable resources faster than they are renewed, may occur, but is not specifically modeled or identified in the renewable resource impact score.

3.2.1.2 Paste solder results

Total Resource Use Impacts by Life-Cycle Stage (Paste Solder)

Table 3-4 and Figure 3.2 present the solder paste results for NRR use impacts by life-cycle stage. Table 3-5 and Figure 3.3 present the solder paste results for RR use impacts by life-cycle stage. The tables list the impact scores per functional unit for the life-cycle stages of each alloy, as well as the percent contribution of each life-cycle stage to the total impacts for each alloy.

Table 3-4. NRR use impacts by life-cycle stage (paste solder)

Life-cycle stage	**SnPb**		**SAC**		**BSA**		**SABC**	
	Score*	%	Score*	%	Score*	%	Score*	%
Upstream	4.79E+01	2.97	3.43E+02	18.9	6.15E+02	34.9	2.42E+02	14.1
Manufacturing	1.89E+01	1.17	2.04E+01	1.12	1.15E+01	0.65	2.04E+01	1.19
Use/application	1.55E+03	95.8	1.45E+03	79.9	1.14E+03	64.5	1.46E+03	84.7
End-of-life	1.23E+00	0.0761	1.06E+00	0.0586	-3.35E-02	-0.0019	1.07E+00	0.0620
Total	**1.61E+03**	**100**	**1.82E+03**	**100**	**1.76E+03**	**100**	**1.72E+03**	**100**

*The impact scores are in units of kilograms of resources/1,000 cc of solder applied to a printed wiring board.

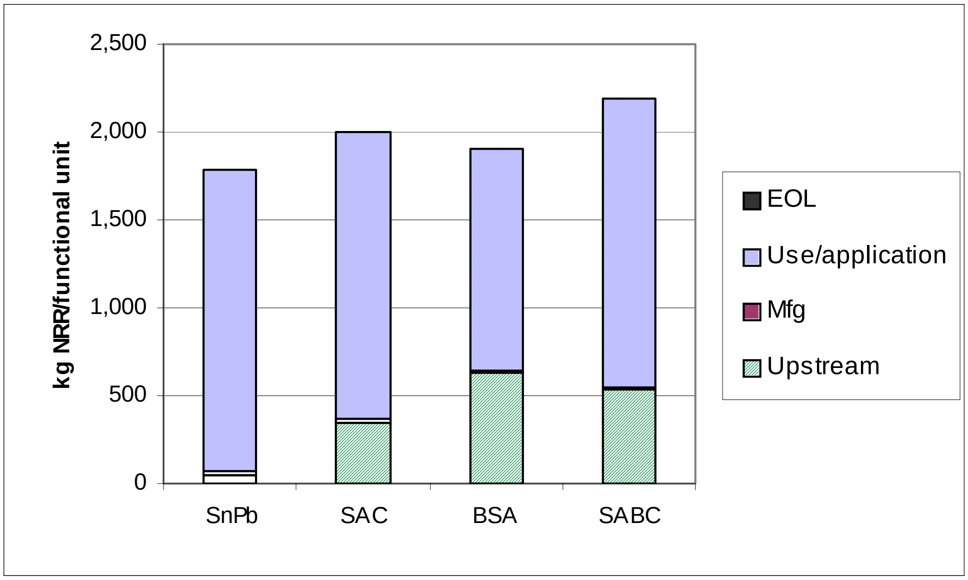


Figure 3-2. Solder Paste Total Life-Cycle Impacts: NRR Use

SAC solder paste has the greatest impact category indicator for NRR use at 1,820 kg of NRR per functional unit, closely followed by BSA and SABC at 1,760 and 1,720 kg of NRR per functional unit, respectively. The indicators for all three lead-free alloys exceed the NRR impact category indicator for SnPb (1,610 kg/functional unit), but only by about 8 to 14 percent[1]. As shown in the table and figure, the use/application stage dominates NRR use impacts for all of the solders, accounting for 65 to 96 percent of NRR use depending on the alloy. The impact scores from the use/application stage include resources consumed to generate electricity for solder application. The upstream life-cycle stage (ME&P) is the second greatest contributor to NRR use for all alloys, accounting for approximately 3 to 35 percent of the total score, depending on the alloy. The manufacturing stage, which includes solder paste manufacturing and post-industrial recycling, contributes minor amounts (approximately 1 percent). The EOL stage is a negligible contributor (less than 0.1 percent) to the overall life-cycle impacts for each alloy.

An interesting note is that although SnPb has the lowest overall NRR impacts compared to all the alternatives, it has the greatest impact from the use/application stage (1,550 kg/functional unit), which is the dominant stage for all of the alloys. This is due to the fact that more electricity is required to reflow 1,000 cc of SnPb solder than the lead-free alloys. Although the melting point of SnPb is lower than SAC and SABC, which taken alone would result in lower energy needs for reflow, the energy requirements on a functional unit basis are greater since SnPb is more dense (e.g., more mass per unit volume of solder is applied to a board). Despite the fact that SnPb has the highest NRR impacts from application, the contribution from upstream processes are greater for the lead-free alternatives than for SnPb, resulting in total NRR impacts for all three alternatives that exceed that of SnPb.

Table 3-5 and Figure 3-3, which present RR use impacts, show a different trend than the NRR impacts. The greatest RR impact category indicator is for SnPb at 34,800 kg/functional unit. The SAC indicator is slightly less at 34,700 kg/functional unit and the SABC indicator follows at 34,100 kg/functional unit. BSA has the lowest total impact score at 26,400 kg/functional unit. The use/application stage dominates each alloy’s life-cycle RR use impacts, accounting for 93 to 99 percent of the total scores. The upstream stage contributes between 0.3 and 6 percent, and the solder manufacturing stage contributes approximately 1 percent to the overall life-cycle impacts of each alloy. The EOL stage is negligible compared to the impact scores from the other stages (e.g., less than 0.1 percent for all).

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[1] The actual difference in the scores from SnPb range from 110 kg to 210 kg of NRR per 1,000 cc of solder applied. To help put this in perspective, say those 110 to 210 kg were made entirely of automobile gasoline, then the amount can be equated to 39 to 75 gallons of automobile gasoline (assuming a density of 2.79 kg/gal). If a driver consumes 20 gallons per week, this would be equivalent to approximately 2 to 4 weeks of driving a car.

Table 3-5. RR use impacts by life-cycle stage (paste solder)

Life-cycle stage	SnPb		SAC		BSA		SABC	
	Score*	%	Score*	%	Score*	%	Score*	%
Upstream	9.60E+01	0.276	2.04E+03	5.87	1.00E+03	3.79	1.32E+03	3.86
Manufacturing	3.70E+02	1.062	3.98E+02	1.15	2.25E+02	0.852	3.98E+02	1.17
Use/application	3.43E+04	98.6	3.22E+04	92.9	2.52E+04	95.3	3.23E+04	94.9
End-of-life	2.75E+01	0.0791	2.38E+01	0.0687	3.52E+00	0.0133	2.39E+01	0.0702
Total	**3.48E+04**	**100**	**3.47E+04**	**100**	**2.64E+04**	**100**	**3.41E+04**	**100**

*The impact scores are in units of kilograms of resources/1,000 cc of solder applied to a printed wiring board

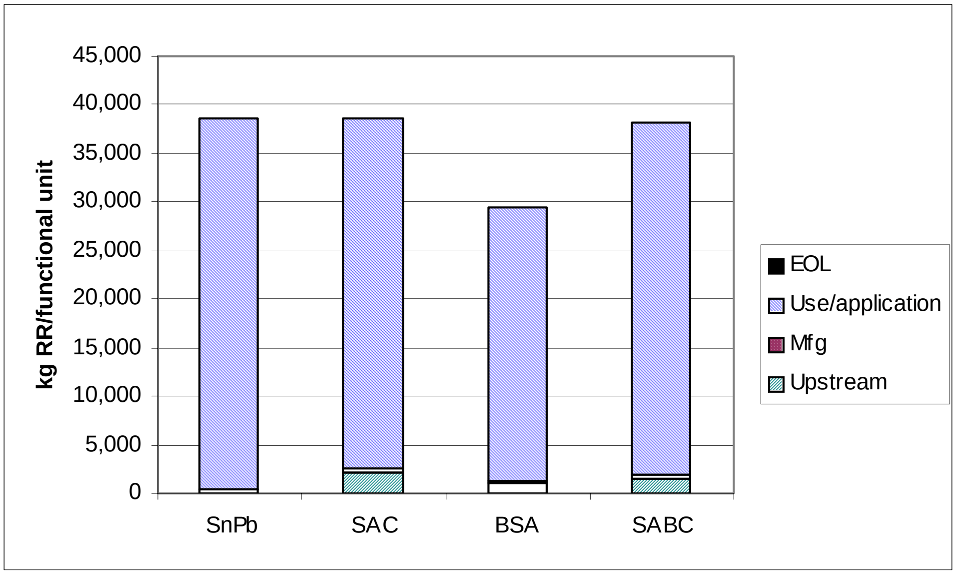

Figure 3-3 Solder Paste Total Life-Cycle Impacts: RR Use

Similar to the NRR use impacts, SnPb has the highest RR impacts from the use/application stage alone; however, the upstream impacts from SAC and SABC cause their total impact scores to slightly exceed that of SnPb. Although BSA's upstream impact score exceeds that of SnPb, BSA still has a smaller total score.

Resource Use Impacts by Process Group (Paste Solder)

Table 3-6 lists the NRR use impacts for the process groups in the life-cycle of a solder. In addition to production processes typically associated with solder manufacturing, process groups include fuel or energy production associated with a particular process (see Table 3-3). Impacts from the use/application stage, which is the dominant stage contributing to the life-cycle impacts, are due entirely to the production of electricity for the solder reflow process.

Upstream impacts arise from the materials consumed in the extraction and processing of the various metals present in the alloys. Of note is that bismuth production for the BSA alloy is the single greatest contributor to upstream NRR use for all of the alloys (507 kg/functional unit), causing BSA to exceed the impact scores of the other three alloys in the upstream stage. As a result, bismuth production (which contributes 27 percent to the overall life-cycle impacts of BSA), and to a much lesser degree, silver production (which contributes 5 percent) cause BSA's overall NRR impacts to exceed SnPb.

Table 3-6. NRR use impacts by life-cycle stage and process group (paste solder)

Life-cycle stage	**SnPb**		**SAC**		**BSA**		**SABC**	
Process group	Score*	%	Score*	%	Score*	%	Score*	%
UPSTREAM								
Sn production	2.34E+01	1.31	3.43E+01	1.72	1.76E+01	0.929	3.46E+01	1.82
Pb production	2.45E+01	1.37	N/A	N/A	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	3.03E+02	15.2	9.04E+01	4.79	1.95E+02	10.2
Cu production	N/A	N/A	6.00E+00	0.300	N/A	N/A	5.02E+00	0.264
Bi production	N/A	N/A	N/A	N/A	5.07E+02	26.8	7.67E+00	0.403
Total	**4.79E+01**	**2.68**	**3.43E+02**	**17.2**	**6.15E+02**	**32.6**	**2.42E+02**	**12.7**
MANUFACTURING								
Solder manufacturing	6.81E+00	0.381	1.04E+01	0.519	6.54E+00	0.346	1.04E+01	0.547
Post-industrial recycling	1.21E+01	0.679	1.01E+01	0.504	4.96E+00	0.263	1.00E+01	0.527
Total	**1.89E+01**	**1.06**	**2.04E+01**	**1.02**	**1.15E+01**	**0.609**	**2.04E+01**	**1.07**
USE/APPLICATION								
Solder application	1.72E+03	96.2	1.63E+03	81.7	1.26E+03	66.8	1.64E+03	86.1
Total	**1.72E+03**	**96.2**	**1.63E+03**	**81.7**	**1.26E+03**	**66.8**	**1.64E+03**	**86.1**
END-OF-LIFE								
Landfill	4.96E-02	0.00278	4.29E-02	0.00215	5.31E-02	0.00281	4.31E-02	0.00227
Incineration	-2.26E-01	-0.0126	-1.95E-01	-0.0098	-2.42E-01	-0.0128	-1.96E-01	-0.0103
Demanufacturing	1.52E-01	0.00851	1.32E-01	0.00659	1.55E-01	0.00820	1.32E-01	0.00695
Cu smelting	1.25E+00	0.0702	1.08E+00	0.0543	N/A	N/A	1.09E+00	0.0573
Unregulated	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00
Total	**1.23E+00**	**0.0688**	**1.06E+00**	**0.0533**	**-3.35E-02**	**-0.0018**	**1.07E+00**	**0.0562**
GRAND TOTAL	**1.79E+03**	**100**	**2.00E+03**	**100**	**1.89E+03**	**100**	**1.90E+03**	**100**

*The impact scores are in units of kilograms of resources/1,000 cc of solder applied to a printed wiring board.
N/A=not applicable

Silver production contributes significantly to the upstream impacts for SAC and SABC, causing these alloys to have greater total impacts than SnPb. Silver processing in SAC and SABC dominates the upstream impacts, even though silver comprises a much smaller percentage of the overall alloy content than tin. For example, SAC is 95.5 percent tin (Sn) and only 3.9 percent silver (Ag), yet its impacts from silver production are far greater than those from tin production (15 percent of total NRR impacts for silver versus 2 percent for tin). This illustrates the relatively high resource consumption of silver extraction and processing compared to the other solder metals. For BSA, the NRR impacts from silver processing account for about 5 percent of total impacts compared to about 27 percent for bismuth processing. In this case, BSA's impacts from silver processing are disproportionately higher than its silver content, but less so than with SAC and SABC. BSA contains 57 percent Bismuth (Bi) and 1 percent Ag.

Manufacturing impacts are small compared to the upstream and use/application life-cycle stages, and are nearly evenly distributed between solder manufacturing and post-industrial recycling for the lead-free alternatives. SnPb, on the other hand, consumes almost 80 percent more NRR in post-industrial recycling than in solder manufacturing. The differences in the distribution of impacts between solder manufacturing and post-industrial recycling among the alloys are due to two factors: (1) there are varying amounts of secondary alloy used in manufacturing each of the alloys, and (2) the alloys have different melting temperatures that affect their relative resource use. SnPb has the greatest amount of secondary alloy used in manufacturing and requires more post-industrial recycling than the lead-free alloys; however, SAC and SABC have higher melting points and, therefore, require more resources per unit of secondary alloy produced. Although BSA has a lower melting point than SnPb, data were not obtained on the resulting differences in resource inputs for post-industrial recycling of BSA; the inputs were assumed to be the same as for SnPb (this is considered a conservative estimate since the melting point of SnPb is higher than that of BSA). A more detailed discussion of this assumption is presented in Section 2.3.

EOL processes contribute less than 0.08 percent of life-cycle NRR impacts for all of the solders, with the majority of the SnPb, SAC, and SABC EOL impact scores coming from smelting processes to recover copper and other valuable metals from waste electronics. No impacts are shown for copper smelting of BSA-containing PWBs because the LFSP LCA assumes these boards are not sent to copper smelting facilities at EOL. Copper smelting is not included in the BSA inventory since its bismuth content exceeds allowable bismuth levels at these facilities (see Chapter 2). Negative impacts from incineration are due to an energy credit for incineration, which creates negative impacts from natural gas production. No resource impacts are shown for unregulated disposal, as the inventory for this process did not include any resource inputs; however, some energy is consumed when waste PWBs are heated to recover solder and components. The amount of energy and associated resources consumed in this process are not known, but they are expected to be small.

Table 3-7 lists the RR use impacts for the process groups in the life-cycle of a solder. As with the NRR use category, impacts from the use/application stage dominate the life-cycle impacts and are due entirely to production of electricity consumed during the solder reflow process.

Upstream impacts arise from the materials consumed in the extraction and processing of the various metals present in the alloys. Silver production dominates the upstream impacts of the silver-containing alloys, despite their relatively low silver content. In addition, the impact scores related to silver processing range from 607 kg/functional unit to 2,030 kg/functional unit, depending on the silver-bearing alloy, while the impact scores from lead in the SnPb alloy are only 96 kg/functional unit.

Manufacturing impacts are small compared to the upstream and use/application life-cycle stages, and are nearly evenly distributed between solder manufacturing and post-industrial recycling for SAC and SABC. SnPb has twice as many RR impacts from post-industrial recycling than from solder manufacturing. BSA, on the other hand, consumes about 23 percent more RR in manufacturing than in post-industrial recycling. As explained above, the discrepancy in the distribution of impacts between SnPb and the lead-free alloys is because SnPb uses more secondary alloy than BSA. In addition, although less secondary alloy is used for manufacturing SAC and SABC, the impacts are affected by the difference in melting temperatures (e.g., SAC and SABC have higher melting temperatures and consume more resources per unit of secondary alloy produced).

Table 3-7. RR use impacts by life-cycle stage and process group (paste solder)

Life-cycle stage	**SnPb**		**SAC**		**BSA**		**SABC**	
Process group	Score*	%	Score*	%	Score*	%	Score*	%
UPSTREAM								
Sn production	3.68E-02	0.0001	5.38E-02	0.0001	2.76E-02	0.0001	5.44E-02	0.0001
Pb production	9.59E+01	0.248	N/A	N/A	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	2.03E+03	5.26	6.07E+02	2.08	1.31E+03	3.43
Cu production	N/A	N/A	3.56E+00	0.0092	N/A	N/A	2.98E+00	0.0078
Bi production	N/A	N/A	N/A	N/A	3.95E+02	1.35	5.97E+00	0.0157
Total	**9.60E+01**	**0.248**	**2.04E+03**	**5.27**	**1.00E+03**	**3.43**	**1.32E+03**	**3.46**
MANUFACTURING								
Solder manufacturing	1.22E+02	0.316	2.06E+02	0.532	1.24E+02	0.424	2.06E+02	0.542
Post-industrial recycling	2.48E+02	0.641	1.92E+02	0.498	1.01E+02	0.347	1.92E+02	0.504
Total	**3.70E+02**	**0.957**	**3.98E+02**	**1.03**	**2.25E+02**	**0.770**	**3.98E+02**	**1.05**
USE/APPLICATION								
Solder application	3.81E+04	98.7	3.62E+04	93.6	2.80E+04	95.8	3.63E+04	95.4
Total	**3.81E+04**	**98.7**	**3.62E+04**	**93.6**	**2.80E+04**	**95.8**	**3.63E+04**	**95.4**
END-OF-LIFE								
Landfill	9.84E-02	0.0003	8.52E-02	0.0002	1.05E-01	0.0004	8.55E-02	0.0002
Incineration	-1.77E-02	-0.00005	-1.53E-02	-0.00004	-1.89E-02	-0.0001	-1.54E-02	-0.00004
Demanufacturing	3.37E+00	0.0087	2.92E+00	0.0076	3.44E+00	0.0118	2.93E+00	0.0077
Cu smelting	2.41E+01	0.0624	2.08E+01	0.0539	N/A	N/A	2.09E+01	0.0549
Unregulated	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00
Total	**2.75E+01**	**0.0713**	**2.38E+01**	**0.0617**	**3.52E+00**	**0.0121**	**2.39E+01**	**0.0628**
GRAND TOTAL	**3.86E+04**	**100**	**3.87E+04**	**100**	**2.92E+04**	**100**	**3.81E+04**	**100**

*The impact scores are in units of kilograms of resources/1,000 cc of solder applied to a printed wiring board.
N/A=not applicable

EOL processes contribute less than 0.08 percent of life-cycle RR impacts for any of the solders, with the majority of SnPb, SAC, and SABC impacts coming from the smelting processes used to recover copper and other valuable metals from waste electronics. As noted previously, the copper smelting process is not included in the BSA inventory. Negative impacts from incineration are due to the energy credit for incineration with energy recovery. No resource impacts are shown for unregulated disposal as the inventory for this process did not include any resource inputs. Some energy is consumed, however, when waste PWBs are heated to recover solder and components. The amount of energy and associated resources consumed in this process are not known, but they are expected to be small compared to other processes.

Top Contributors to Resource Use Impacts (Paste Solder)

Table 3-8 presents the specific materials or flows contributing greater than or equal to 1 percent of NRR use impacts by solder. As expected from the results presented above, the materials used to produce electricity in the use/application stage are the top contributors to overall NRR impacts, with inert rock being the single greatest contributor for all of the solders and hard coal being the second greatest for all alloys, except BSA. Copper ore from bismuth production is the flow with the second greatest contribution to BSA impacts at 24 percent. In addition to resources used to generate electricity in the use/application stage and bismuth production for BSA, input flows from silver production are major contributors to NRR impacts for the lead-free alloys.

Table 3-8. Top contributors to NRR use impacts (paste solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	Use/application	Electricity generation	Inert rock	76.8
	Use/application	Electricity generation	Hard coal (resource)	13.4
	Use/application	Electricity generation	Lignite (resource)	2.72
	Use/application	Electricity generation	Natural gas (resource)	2.11
SAC	Use/application	Electricity generation	Inert rock	64.1
	Use/application	Electricity generation	Hard coal (resource)	11.2
	Upstream	Silver Production	Zinc-lead-copper ore (12%-3%-2%)	7.61
	Upstream	Silver Production	Inert rock	5.15
	Use/application	Electricity generation	Lignite (resource)	2.27
	Use/application	Electricity generation	Natural gas (resource)	1.76
	Upstream	Silver Production	Limestone (calcium carbonate)	1.27
	Upstream	Silver Production	Hard coal (resource)	1.00
BSA	Use/application	Electricity generation	Inert rock	51.7
	Upstream	Bismuth Production	Copper ore (0.14%)	24.4
	Use/application	Electricity generation	Hard coal (resource)	9.01
	Upstream	Silver Production	Zinc - lead - copper ore (12%-3%-2%)	2.34
	Use/application	Electricity generation	Lignite (resource)	1.83
	Upstream	Silver Production	Inert rock	1.59
	Use/application	Electricity generation	Natural gas (resource)	1.42
	Upstream	Bismuth Production	Zinc - copper ore (4.07%-2.59%)	1.33
	Upstream	Bismuth Production	Lead - zinc ore (4.6%-0.6%)	1.02
SABC	Use/application	Electricity generation	Inert rock	67.9
	Use/application	Electricity generation	Hard coal (resource)	11.8
	Upstream	Silver Production	Zinc - lead - copper ore (12%-3%-2%)	5.17
	Upstream	Silver Production	Inert rock	3.50
	Use/application	Electricity generation	Lignite (resource)	2.40
	Use/application	Electricity generation	Natural gas (resource)	1.86

Table 3-9 presents the specific materials or flows contributing greater than or equal to 1 percent of RR use impacts by solder. The top RRs are water and air. As expected from the RR results presented above, resources from electricity production in the use/application stage are the top contributors to overall RR impacts. Water is the single greatest contributor for all of the solders ranging from 84 to 89 percent of all impacts for each alloy. Water consumed in silver and bismuth production also is a top contributor for the lead-free alloys, but the contribution to total impacts for any alloy is less than 6 percent.

Table 3-9. Top contributors to RR use impacts (paste solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	Use/application	Electricity generation	Water	88.8
	Use/application	Electricity generation	Air	9.79
SAC	Use/application	Electricity generation	Water	83.7
	Use/application	Electricity generation	Air	9.22
	Upstream	Silver Production	water	5.33
BSA	Use/application	Electricity generation	Water	85.9
	Use/application	Electricity generation	Air	9.46
	Upstream	Silver Production	Water	2.09
	Upstream	Bismuth Production	Water	1.21
SABC	Use/application	Electricity generation	Water	85.5
	Use/application	Electricity generation	Air	9.42
	Upstream	Silver Production	Water	3.49

3.2.1.3 Bar solder results

Total Resource Use Impacts by Life-Cycle Stage (Bar Solder)

Table 3-10 and Figure 3-4 present the bar solder results for NRR use impacts by life-cycle stage. Table 3-11 and Figure 3-5 present the bar solder results for RR use impacts by life-cycle stage. The tables list the impact scores per functional unit for the life-cycle stages of each alloy, as well as the percent contribution of each life-cycle stage to the total impacts for each alloy.

Table 3-10. NRR use impacts by life-cycle stage (bar solder)

Life-cycle stage	SnPb		SAC		SnCu	
	Score*	%	Score*	%	Score*	%
Upstream	4.46E+01	14.2	5.08E+02	66.1	4.70E+01	15.1
Manufacturing	2.40E+01	7.63	1.16E+01	1.50	1.63E+01	5.23
Use/application	2.45E+02	77.8	2.48E+02	32.2	2.48E+02	79.3
End-of-life	1.38E+00	0.438	1.21E+00	0.157	1.20E+00	0.384
Total	**3.15E+02**	**100**	**7.68E+02**	**100**	**3.12E+02**	**100**

*The impact scores are in units of kilograms of resources/1,000 cc of solder applied to a printed wiring board.

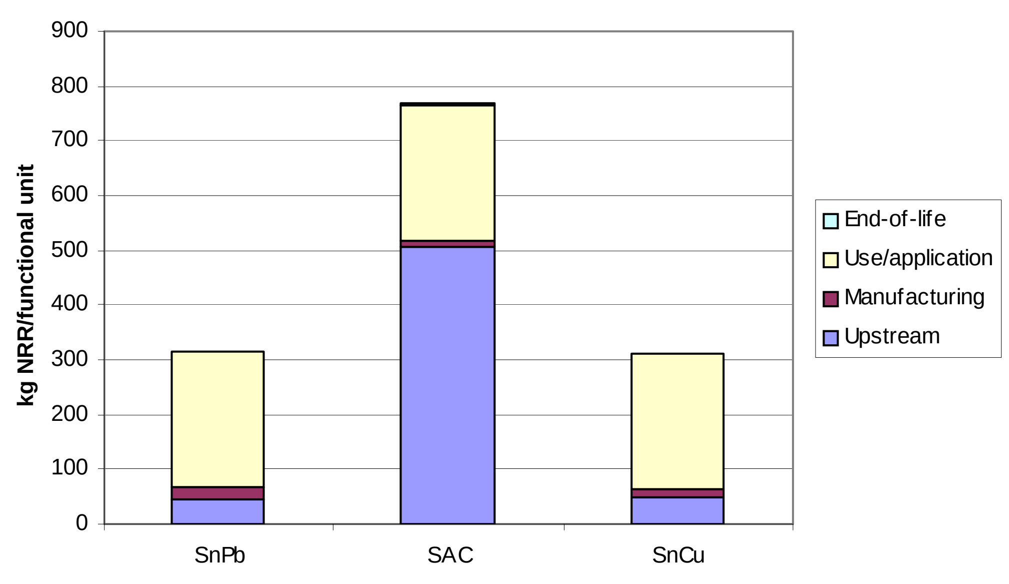

Figure 3-4. Bar Solder Total Life-Cycle Impacts: NRR Use

As was found with the paste solder results, SAC bar solder has the greatest impact category indicator for NRR use. The SAC NRR indicator score is 768 kg of NRR per functional unit, followed by SnPb and SnCu at 315 and 312 kg of NRR per functional unit, respectively[2]. As shown in the table and figure, the upstream stage dominates NRR use impacts for SAC (66 percent), while the use/application stage dominates impacts for SnPb and SnCu. An interesting note is that the use/application stage scores are nearly the same for all three alloys; however, the greatest difference in the total impacts is due to the large impact from the upstream stage for SAC.

Table 3-11 and Figure 3-5, which present RR use impacts, show a similar trend as the NRR impacts in that SAC has the greatest impacts; however, for all three alloys, the use/application stage dominates impacts (ranging from 63 to 94 percent), while the upstream stage is an important contributor to the SAC total impact score (35 percent). As with the NRR use impacts, the use/application stage scores are similar among the three alloys. The upstream impacts from SAC result in a distinguishably greater total impact score compared to SnPb and SnCu (i.e., 45 to 50 percent greater). The differences in absolute scores are 2,730 to 2,930 kg per 1,000 cc of solder applied. To place this in perspective, it is equivalent to 721 to 744 gallons of water (although the impacts are not comprised solely of water).

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[2] The difference between SAC and SnPb is 453 kg of NRR per 1,000 cc of solder applied. If this were all automotive gasoline, this difference is equivalent to 162 gallons of gasoline. Assuming a driver consumes 20 gallons per week, this is also equivalent to approximately 8 weeks of driving.

Table 3-11. RR use impacts by life-cycle stage (bar solder)

Life-cycle stage	SnPb		SAC		SnCu	
	Score*	%	Score*	%	Score*	%
Upstream	8.56E+01	1.42	3.02E+03	34.5	5.90E+00	0.101
Manufacturing	4.85E+02	8.04	2.23E+02	2.55	3.06E+02	5.24
Use/application	5.43E+03	90.0	5.49E+03	62.7	5.49E+03	94.2
End-of-life	3.06E+01	0.507	2.68E+01	0.305	2.66E+01	0.456
Total	**6.03E+03**	**100**	**8.76E+03**	**100**	**5.83E+03**	**100**

*The impact scores are in units of kg of resources/1,000 cc of solder applied to a printed wiring board.

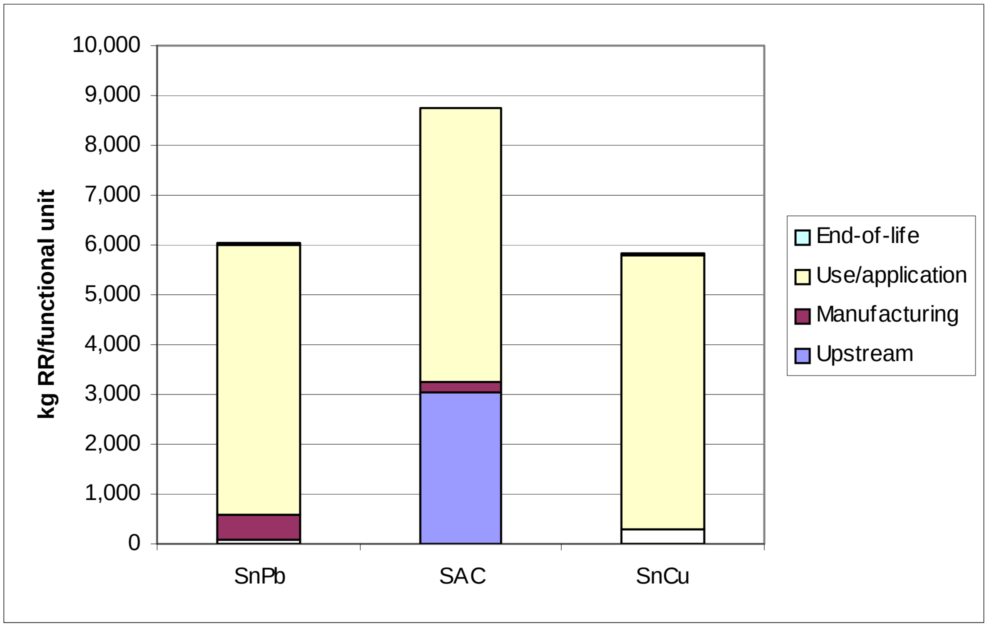


Figure 3-5. Bar Solder Total Life-Cycle Impacts: RR Use

Resource Use Impacts by Process Group (Bar Solder)

Table 3-12 lists the NRR use impacts for the process groups in the life-cycle of a solder. In addition to production processes typically associated with solder manufacturing, process groups include fuel or energy production associated with a particular process (Table 3-3). Impacts from the use/application stage, which is the dominant stage contributing to the life-cycle impacts, are due entirely to the production of electricity for the bar solder application process.

Upstream impacts arise from the materials consumed in the extraction and processing of the various metals present in the alloys. Silver production contributes significantly to the upstream impacts for SAC, causing this alloy to have distinguishably greater total impacts than SnPb and SnCu. Silver processing in SAC dominates the upstream impacts, even though silver comprises a much smaller percentage of the overall alloy content than tin. For example, SAC is

95.5 percent tin and only 3.9 percent silver, yet its impacts from silver production are far greater than those from tin production (59 percent of total NRR impacts for silver versus 6 percent for tin). This illustrates the relatively high resource consumption of silver extraction and processing compared to the other solder metals.

As with the paste solder results, manufacturing impacts are small compared to the upstream and use/application life-cycle stages, and are nearly evenly distributed between solder manufacturing and post-industrial recycling for SAC. SnPb and SnCu, on the other hand, consume more NRR in post-industrial recycling than in solder manufacturing. The differences in the distribution of impacts between solder manufacturing and post-industrial recycling among the alloys are due to two factors: (1) there are varying amounts of secondary alloy used in manufacturing each of the alloys, and (2) the alloys have different melting temperatures that affect their relative resource use. SnPb has the greatest amount of secondary alloy used in manufacturing and requires more post-industrial recycling than the lead-free alloys; however, SAC and SnCu have higher melting points and, therefore, require more resources per unit of secondary alloy produced.

Table 3-12. NRR use impacts by life-cycle stage and process group (bar solder)

Life-cycle stage	**SnPb**		**SAC**		**SnCu**	
Process group	Score*	%	Score*	%	Score*	%
UPSTREAM						
Sn production	2.28E+01	7.23	4.82E+01	6.27	3.72E+01	11.9
Pb production	2.19E+01	6.94	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	4.49E+02	58.5	N/A	N/A
Cu production	N/A	N/A	1.00E+01	1.30	9.83E+00	N/A
Total	**4.46E+01**	**14.2**	**5.08E+02**	**66.1**	**4.70E+01**	**15.1**
MANUFACTURING						
Solder manufacturing	3.60E+00	1.14	5.47E+00	0.713	5.89E+00	1.89
Post-industrial recycling	2.04E+01	6.49	6.08E+00	0.792	1.04E+01	3.34
Total	**2.40E+01**	**7.63**	**1.16E+01**	**1.50**	**1.63E+01**	**5.23**
USE/APPLICATION						
Wave application	2.45E+02	77.8	2.48E+02	32.2	2.48E+02	79.3
Total	**2.45E+02**	**77.8**	**2.48E+02**	**32.2**	**2.48E+02**	**79.3**
END-OF-LIFE						
Landfill	5.51E-02	0.0175	4.83E-02	0.0063	4.79E-02	0.0153
Incineration	-2.38E-01	-0.0755	-2.08E-01	-0.0271	-2.07E-01	-0.0662
Demanufacture	1.69E-01	0.0537	1.48E-01	0.0192	1.47E-01	0.0470
Cu smelting	1.39E+00	0.443	1.22E+00	0.159	1.21E+00	0.388
Unregulated	0.00E+00	0.0000	0.00E+00	0.0000	0.00E+00	0.0000
Total	**1.38E+00**	**0.438**	**1.21E+00**	**0.157**	**1.20E+00**	**0.384**
GRAND TOTAL	**3.15E+02**	**100**	**7.68E+02**	**100**	**3.12E+02**	**100**

*The impact scores are in units of kg resources/1,000 cc of solder applied to a printed wiring board.
N/A=not applicable

As discussed with the paste solder results, EOL processes contribute a very small percent (less than 0.6 percent) of life-cycle NRR impacts for all of the solders, with the majority of the EOL impact scores coming from smelting processes to recover copper and other valuable metals from waste electronics.

Table 3-13 lists the RR use impacts for the process groups in the life-cycle of a solder. Impacts from the use/application stage dominate the life-cycle impacts and are due entirely to the production of electricity consumed during the wave solder application process.

Table 3-13. RR use impacts by life-cycle stage and process group (bar solder)

Life-cycle stage	**SnPb**		**SAC**		**SnCu**	
Process group	Score*	%	Score*	%	Score*	%
UPSTREAM						
Sn production	3.58E-02	0.0006	7.57E-02	0.0009	5.84E-02	0.0010
Pb production	8.56E+01	1.42	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	3.02E+03	34.4	N/A	N/A
Cu production	N/A	N/A	5.95E+00	0.0679	5.84E+00	N/A
Total	**8.56E+01**	**1.42**	**3.02E+03**	**34.5**	**5.90E+00**	**0.101**
MANUFACTURING						
Solder manufacturing	6.80E+01	1.13	1.07E+02	1.22	1.06E+02	1.82
Post-industrial recycling	4.17E+02	6.92	1.16E+02	1.33	2.00E+02	3.42
Total	**4.85E+02**	**8.04**	**2.23E+02**	**2.55**	**3.06E+02**	**5.24**
USE/APPLICATION						
Wave application	5.43E+03	90.0297	5.49E+03	62.6721	5.49E+03	94.1992
Total	**5.43E+03**	**90.0**	**5.49E+03**	**62.7**	**5.49E+03**	**94.2**
END-OF-LIFE						
Landfill	1.09E-01	0.0018	9.57E-02	0.0011	9.50E-02	0.0016
Incineration	-1.86E-02	-0.0003	-1.63E-02	-0.0002	-1.62E-02	-0.0003
Demanufacture	3.75E+00	0.0621	3.28E+00	0.0374	3.26E+00	0.0558
Cu smelting	2.68E+01	0.4437	2.34E+01	0.2672	2.33E+01	0.3987
Unregulated	0.00E+00	0.0000	0.00E+00	0.0000	0.00E+00	0.0000
Total	**3.06E+01**	**0.507**	**2.68E+01**	**0.305**	**2.66E+01**	**0.456**
GRAND TOTAL	**6.03E+03**	**100**	**8.76E+03**	**100**	**5.83E+03**	**100**

*The impact scores are in units of kg resources/1,000 cc of solder applied to a printed wiring board.
N/A=not applicable

Upstream impacts arise from the materials consumed in the extraction and processing of the various metals present in the alloys. Similar to the NRR results, silver production for SAC, which constitutes 34 percent of total RR impacts, dominates the upstream impacts despite its relatively low silver content.

Manufacturing impacts are small compared to the upstream and use/application life-cycle stages, and are nearly evenly distributed between solder manufacturing and post-industrial recycling for SAC. For SnPb and SnCu, the impacts are greater from post-industrial recycling than they are from bar solder manufacturing.

EOL processes contribute less than 0.6 percent of life-cycle RR impacts for all of the solders, with the majority of impacts coming from the smelting processes used to recover copper and other valuable metals from waste electronics (see the earlier discussion for paste and NRR impacts, Section 3.2.1).

Top Contributors to Resource Use Impacts (Bar Solder)

Table 3-14 presents the specific materials or flows contributing greater than or equal to 1 percent of NRR use impacts by solder. As expected from the results presented above, the materials used to produce electricity in the use/application stage are the top contributors to overall NRR impacts for SnPb and SnCu, with inert rock being the single greatest contributor for all of the solders and hard coal being the second greatest. The top two contributors to the SAC impacts are zinc-lead-copper ore from silver production (27 percent) and inert rock from electricity generation in the use/application stage (26 percent).

Table 3-14 Top contributors to NRR use impacts (bar solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	Use/application	Electricity generation	Inert rock	62.3
	Use/application	Electricity generation	Hard coal (resource)	10.9
	Manufacturing	Electricity generation for post-industrial recycling	Inert rock	4.71
	Upstream	Lead production	Lead - zinc ore (4.6%-0.6%)	4.45
	Upstream	Tin production	Hard coal (resource)	2.59
	Use/application	Electricity generation for solder application	Lignite (resource)	2.20
	Upstream	Tin production	Natural gas (resource)	1.79
	Use/application	Electricity generation for solder application	Natural gas (resource)	1.71
	Upstream	Tin production	Crude oil (resource)	1.69
	Upstream	Tin production	Tin ore	1.15
	Upstream	Lead production	Inert rock	1.06
SAC	Upstream	Silver production	Zinc - lead - copper ore (12%-3%-2%)	26.7
	Use/Application	Electricity generation	Inert rock	25.8
	Upstream	Silver production	Inert rock	18.1
	Use/Application	Electricity generation	Hard coal (resource)	4.51
	Upstream	Silver production	Limestone (calcium carbonate)	4.47
	Upstream	Silver production	Hard coal (resource)	3.52
	Upstream	Silver production	Quartz sand (silica sand; silicon dioxide)	2.50
	Upstream	Tin production	Hard coal (resource)	2.25
	Upstream	Tin production	Natural gas (resource)	1.56
	Upstream	Tin production	Crude oil (resource)	1.47
	Upstream	Silver production	Crude oil (resource)	1.32
	Upstream	Copper production	Copper ore (0.14%)	1.17
	Upstream	Silver production	Soil	1.09
	Upstream	Tin production	Tin ore	1.00

Table 3-14 Top contributors to NRR use impacts (bar solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnCu	Use/application	Electricity generation	Inert rock	63.5
	Use/application	Electricity generation	Hard coal (resource)	11.1
	Upstream	Tin production	Hard coal (resource)	4.26
	Upstream	Tin production	Natural gas (resource)	2.95
	Upstream	Copper production	Copper ore (0.14%)	2.83
	Upstream	Tin production	Crude oil (resource)	2.78
	Use/application	Electricity generation	Lignite (resource)	2.25
	Manufacturing	Electricity generation for post-industrial recycling	Inert rock	2.25
	Upstream	Tin production	Tin ore	1.90
	Use/application	Electricity generation	Natural gas (resource)	1.74
	Manufacturing	Electricity generation for solder manufacturing	Inert rock	1.12

Table 3-15 presents the specific materials or flows contributing greater than 1 percent of RR use impacts by solder. The top RRs are water and air. As expected from the RR results presented above, resources from electricity production in the use/application stage are the top contributors to overall RR impacts. Water from electricity generation for wave application is the single greatest contributor for all of the solders ranging from 57 to 85 percent of all impacts for each alloy. Water consumed in silver production also is a top contributor for SAC (31 percent).

Table 3-15. Top contributors to RR use impacts (bar solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	Use/application	Electricity generation	Water	81.1
	Use/application	Electricity generation	Air	8.94
	Manufacturing	Electricity generation for post-industrial recycling	Water	6.13
SAC	Use/application	Electricity generation	Water	56.5
	Upstream	Silver production	Water	31.3
	Use/application	Electricity generation	Air	6.22
	Upstream	Silver production	Air	3.13
	Manufacturing	Electricity generation for post-industrial recycling	Water	1.16
	Manufacturing	Solder manufacturing	Water	1.00
SnCu	Use/application	Electricity generation	Water	84.8
	Use/application	Electricity generation	Air	9.35
	Manufacturing	Electricity generation for post-industrial recycling	Water	3.00
	Manufacturing	Solder manufacturing	Water	1.50

3.2.1.4 Limitations and uncertainties

The renewable and non-renewable resource use results presented here are based on the mass of a material consumed. Depletion of renewable materials, which results from the extraction of RRs faster than they are renewed may occur, but is not specifically modeled or identified in the RR use impact scores. For the NRR use category, depletion occurs from the extraction of these NRRs; however, the impact scores do not relate consumption rates to the Earth's ability to sustain that consumption.

In the paste solder results, the SnPb and lead-free alloy impact scores for both NRR and RR use are being driven by the electricity consumed to power a reflow solder oven in the use/application stage. Electricity consumption data are based on the average of two experimental reflow application runs conducted by the LFSP. The first experimental run was conducted using a 1998 model reflow oven, which is less energy efficient than the 2002 model oven used in the second run. These are primary data collected for the purposes of the LFSP under controlled conditions and are considered to be of good quality. There is considerable variation in the two data points (from 8,170 to 17,100 MJ per functional unit for SnPb, for example), which introduces some uncertainty into the average value used in the LCIA. In addition, while these two data points represent reasonable high and low values, the data are limited. Section 3.3 presents the results of sensitivity analyses of the high and low electricity consumption values for each alloy. Chapter 2 describes limitations and uncertainties in the reflow electricity consumption data in more detail.

In the bar solder results, the energy from wave application also is a major contributor for all alloys; however, silver production for SAC is another major contributor. The energy data from wave application are primary data collected for this study and are expected to be representative of general wave applications, although they are only from one data set. Another source of uncertainty is that the electricity generation process used in this study is from secondary data provided in the GaBi database. Data quality of the electricity generation inventory, as determined by GaBi, is considered "good." In addition, an average U.S. electric grid mix was selected for use in this study to conform and with the data collected from the solder application process (all from the U.S.) and with the geographic boundaries of this study. As a result, use of a secondary data set for electricity generation is not expected to be a large source of uncertainty.

Finally, the secondary data used for silver production is another source of uncertainty. This silver production process is a mix of global data from GaBi, and the data quality is described as "good." Another available data set for silver production (Ecobilan, 1999) suggests possibly significant variations between the two inventories. GaBi data were chosen for this study in part because they were considered of good quality, are representative of relatively recent data (1994-1995), were from the same source as most of the other upstream data sets used in this study, and were from a company that could be easily contacted for questions regarding the data. See Chapter 2 for the discussion on upstream inventory data. Because life-cycle impacts in this and several other impact categories are largely being driven by the inventory for silver production, the DEAM data are used in an alternate analysis to determine the sensitivity of overall LCIA results to the silver inventory. This is discussed further in Section 3.3.

3.2.2 Energy Use

3.2.2.1 Characterization

General energy consumption is used as an indicator of potential environmental impacts from the entire energy generation cycle. Energy use impact scores are based on both *fuel* and *electricity* flows. The impact category indicator is the sum of electrical energy inputs and fuel energy inputs. Fuel inputs are converted from mass to energy units using the fuel's heat value (H) and the density (D), presented in Appendix G. The impact score is calculated by:

$$(IS_E)_i = (Amt_E)_i \text{ or } [Amt_F \times (H / D)]_i$$

where:

IS_E	equals the impact score for energy use (MJ) per functional unit;
Amt_E	equals the inventory input amount of electrical energy used (MJ) per functional unit;
Amt_F	equals the inventory input amount of fuel used (kg) per functional unit;
H	equals the heat value of fuel *i* (MJ/L); and
D	equals the density of fuel *i* (kg/L).

This category addresses energy *use* only. The emissions from energy production are outputs from the energy production process and are classified to applicable impact categories, depending on the disposition and chemical properties of the outputs (see Classification Section 3.1.1).

3.2.2.2 Paste solder results

Total Energy Use Impacts by Life-Cycle Stage (Paste Solder)

Table 3-16 presents the solder paste results for energy use impacts by life-cycle stage, based on the impact assessment methodology presented above. Figure 3-6 presents the results in a stacked bar chart. General energy consumption is used as an indicator of potential environmental impacts from the entire energy generation cycle.

Table 3-16. Energy use impacts by life-cycle stage (paste solder)

Life-Cycle Stage	**SnPb**		**SAC**		**BSA**		**SABC**	
	Score*	%	Score*	%	Score*	%	Score*	%
Upstream	8.67E+02	6.94	2.61E+03	19.3	1.25E+03	12.8	2.12E+03	16.2
Manufacturing	2.13E+02	1.70	2.29E+02	1.69	1.29E+02	1.33	2.29E+02	1.75
Use/application	1.14E+04	91.2	1.07E+04	78.9	8.37E+03	85.8	1.07E+04	82.0
End-of-life	1.68E+01	0.135	1.46E+01	0.107	2.49E+00	0.0255	1.46E+01	0.112
Total	**1.25E+04**	**100**	**1.36E+04**	**100**	**9.76E+03**	**100**	**1.31E+04**	**100**

*The impact scores are in units of megajoules/1,000 cc of solder applied to a printed wiring board.

SAC solder paste has the greatest impact category indicator for energy use at 13,600 MJ per functional unit, closely followed by SABC at 13,100 MJ, and SnPb at 12,500 MJ. BSA is the only solder paste that consumes substantially less energy (9,760 MJ per functional unit), primarily due to its lower melting temperature that significantly reduces energy consumption during solder application. For a relative comparison, the average U.S. household consumes approximately 9,244 MJ of energy per month (DOE, 2003). As shown in the table and figure, the use/application stage dominates energy use impacts for all of the solders, accounting for 79 to 91 percent of energy use depending on the alloy.

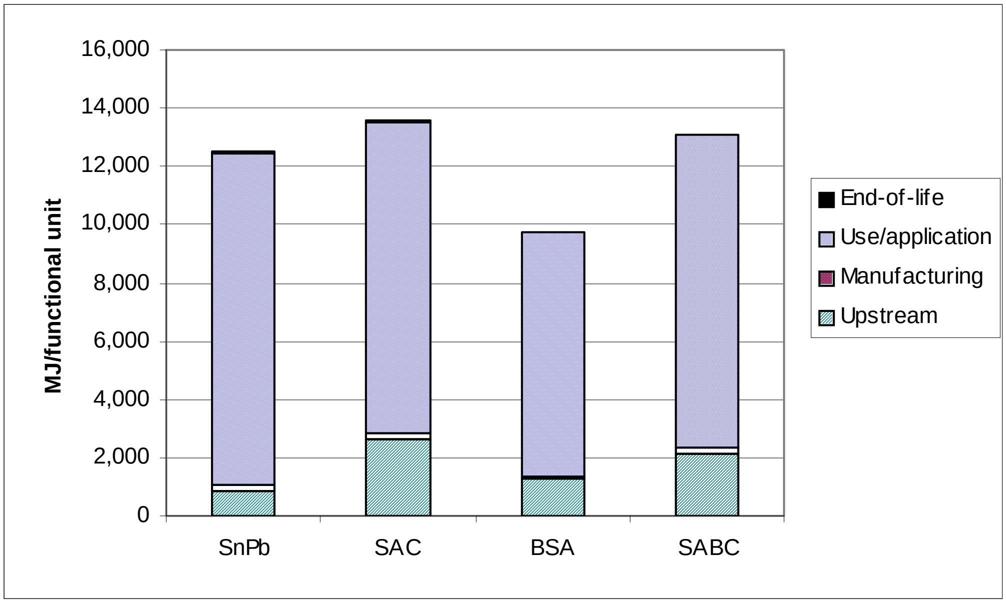


Figure 3-6. Paste Solder Total Life-Cycle Impacts: Energy Use

SnPb, which has a higher melting temperature than BSA but a lower melting temperature than SAC and SABC, requires the most energy in the use/application stage (11,400 MJ/functional unit). This phenomenon is due to the greater density of the alloy. Although SAC and SABC have higher melting temperatures and require more energy per unit mass of solder, the higher density of SnPb requires more energy per unit of volume, causing the use/application stage energy impacts on a functional unit basis to be slightly greater for SnPb than for the higher melting temperature alloys. Total energy consumption for SnPb, however, is less than that of SAC and SABC because SnPb upstream processes are less energy-intensive. SnPb upstream processes (e.g., ME&P) consume 867 MJ/functional unit compared to 2,610 MJ/functional unit for SAC, 1,250 MJ/functional unit for BSA, and 2,120 MJ/functional unit for SABC. Solder manufacturing and EOL processes combined consume less than two percent of the life-cycle energy of any of the solders.

Energy Use Impacts by Process Group (Paste Solder)

Table 3-17 lists the energy use impacts of each of the processes in the life-cycle of a solder. Energy impacts in the use/application stage are due entirely to electricity consumed in the solder reflow process. Upstream energy impacts, on the other hand, arise from the energy consumed in the extraction and processing of the various metals present in the alloys. Of note is that energy impacts from silver processing approach impacts from tin processing in solders that contain both metals, even though the silver content of the alloys is much less than the tin content. For example, SAC is 95.5 percent Sn and only 3.9 percent Ag, yet its impacts from silver production are nearly as great as those from tin production. This illustrates the relatively high energy intensity of silver extraction and processing compared to the other solder metals.

Table 3-17. Energy use impacts by life-cycle stage and process group (paste solder)

Life-Cycle Stage	**SnPb**		**SAC**		**BSA**		**SABC**	
Process group	Score*	%	Score*	%	Score*	%	Score*	%
UPSTREAM								
Sn production	5.84E+01	0.467	1.18E+03	8.73	6.06E+02	6.21	1.19E+03	9.11
Pb production	8.09E+02	6.47	N/A	N/A	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	1.42E+03	10.5	4.25E+02	4.36	9.17E+02	7.00
Cu production	N/A	N/A	1.94E+00	0.0143	N/A	N/A	1.62E+00	0.0124
Bi production	N/A	N/A	N/A	N/A	2.21E+02	2.26	3.34E+00	0.0255
Total	**8.67E+02**	**6.94**	**2.61E+03**	**19.3**	**1.25E+03**	**12.8**	**2.12E+03**	**16.2**
MANUFACTURING								
Solder manufacturing	9.52E+01	0.762	1.14E+02	0.840	8.11E+01	0.832	1.14E+02	0.873
Post-industrial recycling	1.18E+02	0.942	1.15E+02	0.851	4.82E+01	0.494	1.15E+02	0.878
Total	**2.13E+02**	**1.70**	**2.29E+02**	**1.69**	**1.29E+02**	**1.33**	**2.29E+02**	**1.75**
USE/APPLICATION								
Reflow application	1.14E+04	91.2	1.07E+04	78.9	8.37E+03	85.8	1.07E+04	82.0
Total	**1.14E+04**	**91.2%**	**1.07E+04**	**78.9**	**8.37E+03**	**85.8**	**1.07E+04**	**82.0**
END-OF-LIFE								
Landfill	1.67E+00	0.0134	1.45E+00	0.0107	1.79E+00	0.0183	1.45E+00	0.0111
Incineration	-4.10E-01	-0.0033	-3.55E-01	-0.0026	-4.39E-01	-0.0045	-3.57E-01	-0.0027
Demanufacturing	1.12E+00	0.0090	9.69E-01	0.0072	1.14E+00	0.0117	9.73E-01	0.0074
Cu smelting	1.44E+01	0.116	1.25E+01	0.0922	N/A	N/A	1.25E+01	0.0957
Unregulated	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00
Total	**1.68E+01**	**0.135**	**1.46E+01**	**0.107**	**2.49E+00**	**0.0255**	**1.46E+01**	**0.112**
GRAND TOTAL	**1.25E+04**	**100**	**1.36E+04**	**100**	**9.76E+03**	**100**	**1.31E+04**	**100**

*The impact scores are in units of megajoules/1,000 cc of solder applied to a printed wiring board.
N/A=not applicable

Manufacturing energy impacts are small compared to the upstream and use/application life-cycle stages, and are almost evenly distributed between solder manufacturing and post-industrial recycling. An exception is BSA, which consumes less energy in post-industrial processing (recycling) of the secondary alloy than in solder manufacturing. As discussed in Section 3.2.2.1, less secondary BSA is used in solder manufacturing, and as a result less post-industrial processing occurs. Therefore, the BSA solder manufacturing process is a greater contributor to the BSA manufacturing stage score than is post-industrial recycling. The difference is ostensibly made up by the increase in primary production of the metals in BSA (e.g., upstream impacts). SAC and SABC also have less secondary metals production than SnPb, but they consume nearly as much energy in post-industrial recycling as SnPb due to their higher melting temperatures.

EOL processes contribute less than 0.2 percent of life-cycle energy impacts for any of the solders, with the majority of SnPb, SAC, and SABC impacts at EOL coming from smelting processes to recover copper and other valuable metals from waste electronics. As noted previously, a copper smelter process is not included in the BSA inventory due to its high bismuth content, which is unacceptable to copper smelters. Negative energy impacts from incineration are due to an energy credit for incineration with energy recovery. No energy impacts are shown for unregulated disposal, as the inventory for this process did not include any resource inputs. Some energy is consumed, however, when waste PWBs are heated to recover solder and components. The amount of energy and associated resources consumed in this process are not known, but they are expected to be small compared to other processes.

Top Contributors to Energy Use Impacts (Paste Solder)

Table 3-18 presents the specific materials or flows contributing greater than or equal to 1 percent of the total energy impact category indicators by solder. As expected from the results presented above, the fuels used to produce electricity in the use/application stage are the top contributors to overall energy impacts, with hard coal being the single greatest contributor for all of the solders. Per the GaBi inventory employed in this study for electricity generation, coal is the primary fuel used in the U.S. electric grid, accounting for 52 percent of electricity generation (PE & IKP, 2000). Uranium used to generate nuclear power in the use/application stage is the next largest contributor for all solders, again because uranium is the next largest fuel in the U.S. electric grid (23 percent of the U.S. power grid is from nuclear fuel). In addition to fuels used to generate electricity in the use/application stage, other major contributors to energy impacts include fuels used in tin and silver extraction and processing. The extraction and processing inventories are from secondary data sources that do not distinguish whether these fuels are used to produce electricity consumed during extraction and processing or used directly in these processes.

Table 3-18. Top contributors to energy use impacts (paste solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	Use/application	Electricity generation	Hard coal (resource)	46.8
	Use/application	Electricity generation	Uranium (resource)	23.6
	Use/application	Electricity generation	Natural gas (resource)	11.9
	Use/application	Electricity generation	Crude oil (resource)	4.14
	Use/application	Electricity generation	Lignite (resource)	3.29
	Upstream	Tin production	Hard coal (resource)	1.95
	Upstream	Tin production	Natural gas (resource)	1.91
	Upstream	Tin production	Crude oil (resource)	1.87
	Use/application	Electricity generation	Primary energy from hydro power	1.50
SAC	Use/application	Electricity generation	Hard coal (resource)	40.5
	Use/application	Electricity generation	Uranium (resource)	20.4
	Use/application	Electricity generation	Natural gas (resource)	10.3
	Upstream	Silver production	Hard coal (resource)	3.80
	Use/application	Electricity generation	Crude oil (resource)	3.58
	Use/application	Electricity generation	Lignite (resource)	2.85
	Upstream	Silver production	Uranium (resource)	2.63
	Upstream	Tin production	Hard coal (resource)	2.63
	Upstream	Tin production	Natural gas (resource)	2.58
	Upstream	Tin production	Crude oil (resource)	2.53
	Upstream	Silver production	Crude oil (resource)	2.13
	Upstream	Silver production	Primary energy from hydro power	1.47
	Use/application	Electricity generation	Primary energy from hydro power	1.29
	Upstream	Tin production	Uranium (resource)	1.00
BSA	Use/application	Electricity generation	Hard coal (resource)	44.0
	Use/application	Electricity generation	Uranium (resource)	22.2
	Use/application	Electricity generation	Natural gas (resource)	11.2
	Use/application	Electricity generation	Crude oil (resource)	3.90
	Use/application	Electricity generation	Lignite (resource)	3.10
	Upstream	Tin production	Hard coal (resource)	1.87
	Upstream	Tin production	Natural gas (resource)	1.84
	Upstream	Tin production	Crude oil (resource)	1.80
	Upstream	Silver production	Hard coal (resource)	1.58
	Use/application	Electricity generation	Primary energy from hydro power	1.41
	Upstream	Silver production	Uranium (resource)	1.09
SABC	Use/application	Electricity generation	Hard coal (resource)	42.0
	Use/application	Electricity generation	Uranium (resource)	21.2
	Use/application	Electricity generation	Natural gas (resource)	10.7
	Use/application	Electricity generation	Crude oil (resource)	3.72
	Use/application	Electricity generation	Lignite (resource)	2.96
	Upstream	Tin production	Hard coal (resource)	2.75
	Upstream	Tin production	Natural gas (resource)	2.69
	Upstream	Tin production	Crude oil (resource)	2.64
	Upstream	Silver production	Hard coal (resource)	2.53
	Upstream	Silver production	Uranium (resource)	1.75
	Upstream	Silver production	Crude oil (resource)	1.42
	Use/application	Electricity generation	Primary energy from hydro power	1.34
	Upstream	Tin production	Uranium (resource)	1.04

3.2.2.3 Bar solder results

Total Energy Use Impacts by Life-Cycle Stage (Bar Solder)

Table 3-19 presents the bar solder results for energy use impacts by life-cycle stage, based on the impact assessment methodology presented above. Figure 3-7 presents the results in a stacked bar chart. General energy consumption is used as an indicator of potential environmental impacts from the entire energy generation cycle.

Table 3-19. Energy use impacts by life-cycle stage (bar solder)

Life-cycle stage	**SnPb**		**SAC**		**SnCu**	
	Score*	%	Score*	%	Score*	%
Upstream	8.38E+02	28.8	3.78E+03	65.5	1.29E+03	37.7
Manufacturing	2.48E+02	8.52	1.47E+02	2.55	2.86E+02	8.39
Use/application	1.80E+03	62.0	1.82E+03	31.6	1.82E+03	53.4
End-of-life	1.87E+01	0.644	1.64E+01	0.284	1.63E+01	0.476
Total	**2.91E+03**	**100**	**5.77E+03**	**100**	**3.41E+03**	**100**

*The impact scores are in units of megajoules/1,000 cc of solder applied to a printed wiring board.

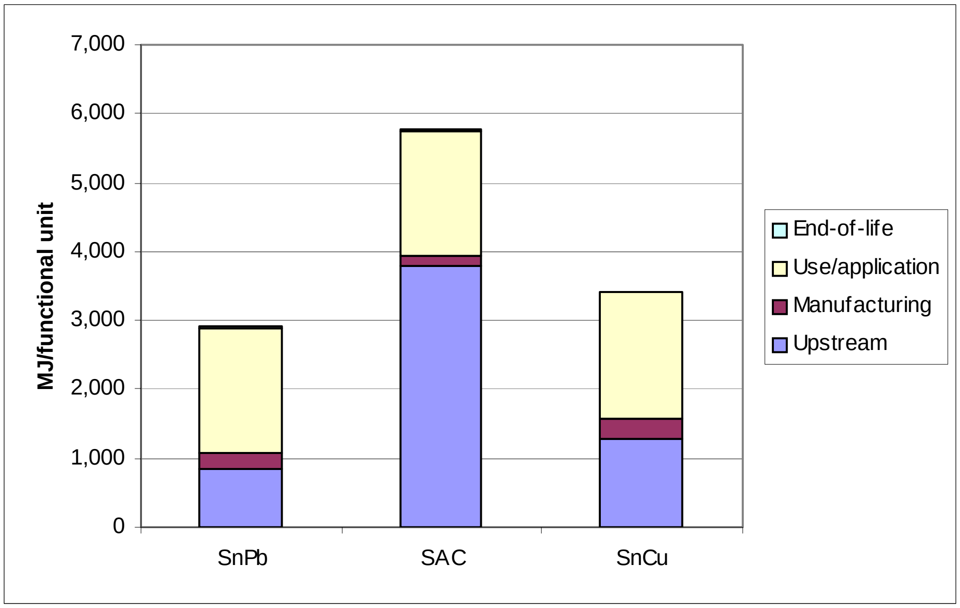


Figure 3-7. Bar Solder Total Life-Cycle Impacts: Energy Use

SAC solder paste has the greatest impact category indicator for energy use at 5,770 MJ per functional unit, followed by SnCu at 3,410 MJ, and SnPb at 2,910 MJ. The ME&P (upstream) life-cycle stage drives the SAC energy results (contributing 66 percent) and causes it to dominate over the other two alloys. The use/application stage energy is the top contributor to SnPb and SnCu energy impacts and the second greatest contributor to SAC energy impacts. SAC and SnCu wave application energy are equal to one another and SnPb application energy is slightly less. The lower wave application energy for SnPb is due to its lower melting temperature; however, it is only slightly lower due to SnPb's higher density than SAC and SnCu. Solder manufacturing consumes between 3 and 9 percent of the life-cycle energy; and EOL processes consume less than 1 percent of the life-cycle energy of any of the solders.

Energy Use Impacts by Process Group (Bar Solder)

Table 3-20 lists the energy use impacts of each of the process groups in the life-cycle of a solder. Upstream energy impacts arise from the energy consumed in the extraction and processing of the various metals present in the alloys. Energy impacts from tin and silver processing are the largest upstream contributing processes. For SAC, energy impacts from silver processing are greater than impacts from tin processing, even though the silver content of the alloys is much less than that of the tin. That is, SAC is 95.5 percent tin and only 3.9 percent silver, yet its impacts from silver production are greater than those from tin production. This illustrates the relatively high energy intensity of silver extraction and processing compared to the other solder metals. Energy impacts in the use/application stage are due entirely to electricity consumed in the wave solder process.

Table 3-20. Energy use impacts by life-cycle stage and process group (bar solder)

Life-cycle stage	**SnPb**		**SAC**		**SnCu**	
Process group	Score*	%	Score*	%	Score*	%
UPSTREAM						
Sn production	7.86E+02	27.0	1.66E+03	28.8	1.28E+03	37.6
Pb production	5.21E+01	1.79	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	2.11E+03	36.7	N/A	N/A
Cu production	N/A	N/A	3.23E+00	0.0560	3.17E+00	N/A
Total	**8.38E+02**	**28.8**	**3.78E+03**	**65.5**	**1.29E+03**	**37.7**
MANUFACTURING						
Solder manufacturing	4.94E+01	1.70	7.74E+01	1.34	9.60E+01	2.81
Post-industrial recycling	1.98E+02	6.82	6.98E+01	1.21	1.90E+02	5.58
Total	**2.48E+02**	**8.52**	**1.47E+02**	**2.55**	**2.86E+02**	**8.39**
USE/APPLICATION						
Solder application	1.80E+03	62.0	1.82E+03	31.6	1.82E+03	53.4
Total	**1.80E+03**	**62.0**	**1.82E+03**	**31.6**	**1.82E+03**	**53.4**
END-OF-LIFE						
Landfill	1.86E+00	0.0640	1.63E+00	0.0282	1.62E+00	0.0473
Incineration	-4.32E-01	-0.0148	-3.78E-01	-0.0066	-3.75E-01	-0.0110
Demanufacturing	1.24E+00	0.0428	1.09E+00	0.0189	1.08E+00	0.0317
Cu smelting	1.60E+01	0.552	1.40E+01	0.243	1.39E+01	0.408
Unregulated	0.00E+00	0.0000	0.00E+00	0.0000	0.00E+00	0.0000
Total	**1.87E+01**	**0.644**	**1.64E+01**	**0.284**	**1.63E+01**	**0.476**
GRAND TOTAL	**2.91E+03**	**100**	**5.77E+03**	**100**	**3.41E+03**	**100**

*The impact scores are in units of megajoules/1,000 cc of solder applied to a printed wiring board.
N/A=not applicable

Manufacturing energy impacts are relatively small compared to the upstream and use/application life-cycle stages. Of the two process groups in the manufacturing stage, post-industrial recycling impacts are greater than the solder manufacturing process group for SnPb and SnCu. The SnPb post-industrial recycling process group contribution is four times (400 percent) greater than the SnPb solder manufacturing group; and the SnCu post-industrial recycling process group contribution is 25 percent greater than the SnCu solder manufacturing process group. For SAC, the post-industrial recycling process group contributes approximately 11 percent *less than* that from solder manufacturing. The reason SnPb and SnCu have greater post-industrial impacts than solder manufacturing (as compared to SAC) is because SnPb and SnCu are assumed to have greater recycled content (coming from post-industrial recycling). The recycled content for individual solders is based on averages taken from primary data collected from solder manufacturers. SnPb has the greatest recycled content percent of all three alloys, which explains the larger difference between PI recycling and solder manufacturing for SnPb compared to the other alloys. In the cases where there is less secondary (recycled) metal, and thus more primary (virgin) metal, there is more primary production of the metals, which translates into impacts in the upstream life-cycle stage.

EOL processes contribute less than 0.6 percent of life-cycle energy impacts for any of the solders, with the majority of SnPb, SAC, and SABC impacts at EOL coming from smelting processes to recover copper and other valuable metals from waste electronics. Negative energy impacts from incineration are due to an energy credit for incineration with energy recovery. No energy impacts are shown for unregulated disposal, as the inventory for this process did not include any resource inputs. Some energy is consumed, however, when waste PWBs are heated to recover solder and components. The amount of energy and associated resources consumed in this process are not quantitatively known, but they are expected to be small compared to other processes.

Top Contributors to Energy Use Impacts (Bar Solder)

Table 3-21 presents the specific materials or flows contributing greater than or equal to 1 percent of the total energy impact category indicators by bar solder. As expected from the results presented above, the fuels used to produce electricity in the use/application stage are the top contributors to overall energy impacts, with hard coal being the single greatest contributor for all of the solders. As described under the paste solder results, per the GaBi inventory employed in this study for electricity generation, coal is the primary fuel used in the U.S. electric grid. In addition to fuels used to generate electricity in the use/application stage, other major contributors to energy impacts include fuels used in silver and tin extraction and processing. The extraction and processing inventories are from secondary data sources that do not distinguish whether these fuels are used to produce electricity consumed during extraction and processing or used directly in these processes.

Table 3-21. Top contributors to energy use impacts (bar solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	Use/application	Electricity generation	Hard coal (resource)	31.8
	Use/application	Electricity generation	Uranium (resource)	16.0
	Upstream	Tin production	Hard coal (resource)	8.14
	Use/application	Electricity generation	Natural gas (resource)	8.12
	Upstream	Tin production	Natural gas (resource)	7.98
	Upstream	Tin production	Crude oil (resource)	7.82
	Upstream	Tin production	Uranium (resource)	3.08
	Use/application	Electricity generation	Crude oil (resource)	2.82
	Manufacturing	Electricity generation for post-industrial recycling	Hard coal (resource)	2.41
	Use/application	Electricity generation	Lignite (resource)	2.24
	Manufacturing	Heavy fuel oil (#6) production for post-industrial recycling	Crude oil (resource)	1.70
	Manufacturing	Electricity generation for post-industrial recycling	Uranium (resource)	1.21
	Use/application	Electricity generation	Primary energy from hydro power	1.02
SAC	Use/application	Electricity generation	Hard coal (resource)	16.2
	Upstream	Silver production	Hard coal (resource)	13.3
	Upstream	Silver production	Uranium (resource)	9.19
	Upstream	Tin production	Hard coal (resource)	8.69
	Upstream	Tin production	Natural gas (resource)	8.52
	Upstream	Tin production	Crude oil (resource)	8.35
	Use/application	Electricity generation	Uranium (resource)	8.19
	Upstream	Silver production	Crude oil (resource)	7.43
	Upstream	Silver production	Primary energy from hydro power	5.11
	Use/application	Electricity generation	Natural gas (resource)	4.14
	Upstream	Tin production	Uranium (resource)	3.29
	Use/application	Electricity generation	Crude oil (resource)	1.44
	Upstream	Silver production	Natural gas (resource)	1.16
	Use/application	Electricity generation	Lignite (resource)	1.14
SnCu	Use/application	Electricity generation	Hard coal (resource)	28.0
	Use/application	Electricity generation	Uranium (resource)	14.1
	Upstream	Tin production	Hard coal (resource)	11.6
	Upstream	Tin production	Natural gas (resource)	11.4
	Upstream	Tin production	Crude oil (resource)	11.1
	Use/application	Electricity generation	Natural gas (resource)	7.15
	Upstream	Tin production	Uranium (resource)	4.39
	Use/application	Electricity generation	Crude oil (resource)	2.48
	Use/application	Electricity generation	Lignite (resource)	1.97
	Manufacturing	Heavy fuel oil (#6) production for post-industrial recycling	Crude oil (resource)	1.40
	Manufacturing	Natural gas production for solder manufacturing	Natural gas (resource)	1.37

3.2.2.4 Limitations and uncertainties

The major contributors to energy impacts are from electricity generation used during the use/application stage (particularly for paste solders) and from upstream materials extraction processes (particularly for SAC bar solder). Similar to the discussion in Section 3.2.1, where electricity generation for reflow application is concerned, the same uncertainties apply: (1) the number of data points used to estimate reflow electricity consumption are limited and cover a large range, and (2) electricity production data are from a secondary source. With regard to the first source of uncertainty, the amount of electricity consumed during reflow was measured during reflow testing conducted by the LFSP. These are primary data collected under controlled conditions to meet the goals and objectives of this study and represent good high and low estimates of wave electricity consumption; however, because the value used in this baseline analysis is averaged from a limited amount of data (two data points for each solder), a sensitivity analysis was performed using the high and low values (see Section 3.3). On the other hand, uncertainties from the use of secondary data for electricity generation are not considered large enough to warrant a separate sensitivity analysis.

For wave application results, primary data were also collected for the solder application process through a controlled testing protocol. Although data from only one test run were used, these data were compared to other known testing data and are expected to be representative of typical wave operations, thus introducing little uncertainty. The use of the secondary data for the electricity generation data was discussed above in the preceding paragraph.

Uncertainties related to the use of upstream data were discussed in Section 3.2.1 and also apply here, particularly to the silver production data for the SAC bar solder results. GaBi gives the silver production data “good” quality rating; however, due to its large impact on the life-cycle of the bar solder results, sensitivity analyses using an alternative data set were conducted (see Section 3.3).

3.2.3 Landfill Space Use Impacts

3.2.3.1 Characterization

Landfill impacts are calculated using solid and hazardous waste flows to land as the volume of landfill space is consumed. This category includes both solid waste and hazardous waste landfill use. For solid waste landfill use, this category pertains to the use of suitable and designated landfill space as a natural resource where municipal waste or construction debris is accepted. For hazardous waste landfill use, this category pertains to the use of suitable and designated landfill space as a natural resource where hazardous waste, as designated and regulated under the Resource Conservation and Recovery Act (RCRA), is accepted. For non-U.S. activities, equivalent hazardous or special waste landfills are considered for this impact category. Impact scores are characterized from solid and hazardous waste outputs with a disposition of landfill. Impact characterization is based on the volume of waste, determined from the inventory mass amount of waste and material density of each specific hazardous waste type:

$$(IS_L)_i = (Amt_W / D)_i$$

where:

IS_L	equals the impact score for landfill (L) use for waste *i* cubic meters (m^3) per functional unit;
Amt_W	equals the inventory output amount of solid waste *i* (kg) per functional unit; and
D	equals density of waste *i* (kg/m^3).

3.2.3.2 Paste solder results

Total Landfill Space Use Impacts by Life-Cycle Stage (Paste Solder)

Table 3-22 presents the solder paste results for landfill space use impacts by life-cycle stage, based on the impact assessment methodology presented above. This impact category includes both hazardous and non-hazardous waste landfills. The table lists the impact scores per functional unit, as well as the percent contribution of each life-cycle stage to the total impacts for each alloy. Figure 3-8 presents the results in a stacked bar chart.

Table 3-22. Landfill space use impacts by life-cycle stage (paste solder)

Life-cycle stage	**SnPb**		**SAC**		**BSA**		**SABC**	
	Score*	%	Score*	%	Score*	%	Score*	%
Upstream	4.20E-05	1.53%	1.36E-02	83.9%	4.37E-03	66.6%	8.73E-03	77.0%
Manufacturing	7.68E-05	2.79%	9.02E-05	0.558%	4.21E-05	0.642%	9.01E-05	0.795%
Use/application	1.81E-03	65.8%	1.70E-03	10.5%	1.33E-03	20.3%	1.71E-03	15.1%
End-of-life	8.23E-04	29.9%	8.13E-04	5.03%	8.24E-04	12.5%	8.12E-04	7.16%
Total	**2.75E-03**	**100%**	**1.62E-02**	**100%**	**6.57E-03**	**100%**	**1.13E-02**	**100%**

*The impact scores are in units of cubic meters of landfill space/1,000 cc of solder applied to a printed wiring board.

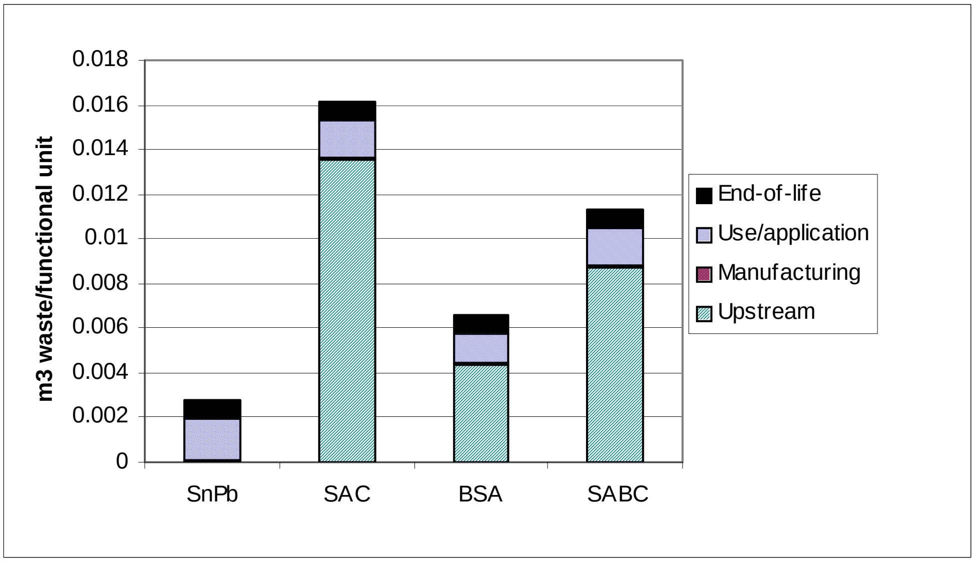


Figure 3-8. Paste Solder Total Life-Cycle Impacts: Landfill Space Use

SAC solder paste has the greatest impact category indicator for landfill space use at 0.0162 m^3 per functional unit, followed by SABC at 0.0113 m^3, BSA at 0.00657 m^3, and SnPb at 0.00275 m^3 per functional unit. The upstream life-cycle stage dominates the total landfill space scores of the lead-free alloys, accounting for 67 to 84 percent of the totals. SnPb landfill space impacts, on the other hand, are dominated by the use/application stage at 66 percent of its total score, followed by the EOL stage at 30 percent. The use/application stage is the second greatest contributor for the lead-free alloys, followed by the EOL stage. The solder manufacturing stage contributes less then 3 percent for any of the solder alloys.

To put these volumes of landfill space into perspective, in 2001, U.S. residents, businesses, and institutions produced more than 229 million tons of municipal solid waste, which is approximately 4.4 pounds (2 kg) per person per day (EPA, 2004). Assuming an average bulk density of 445 kg/m^3 (Franklin Associates, 1999), this equates to approximately 0.0045 m^3 of landfill space. This value falls between the life-cycle landfill space impacts per functional unit for SnPb and BSA.

Landfill Space Use Impacts by Process Group (Paste Solder)

Table 3-23 lists the landfill space use impacts of each of the process groups in the life-cycle of a solder paste. Landfill space use impacts are driven by the upstream processes for the lead-free alloys that alone exceed the total impacts from SnPb. The silver production process contributes between 60 and 83 percent of the total life-cycle landfill space use impacts. This is of interest as the composition of silver in those alloys is relatively small (between 1 and 3.9 percent), suggesting that the silver production process generates more landfilled waste per unit of metal produced than the other metals. For the SnPb alloy, the upstream processes contribute only about 1.4 percent to the total impacts, while it is the reflow application process group (e.g., reflow application and associated electricity generation) that contributes the most to total impacts.

Table 3-23. Landfill space use impacts by life-cycle stage and process group (paste solder)

Life-cycle stage	**SnPb**		**SAC**		**BSA**		**SABC**	
Process group	Score*	%	Score*	%	Score*	%	Score*	%
UPSTREAM								
Sn production	5.16E-06	0.175	7.55E-06	0.0461	3.87E-06	0.0576	7.62E-06	0.0660
Pb production	3.68E-05	1.25	N/A	N/A	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	1.35E-02	82.7	4.04E-03	60.2	8.72E-03	75.4
Cu production	N/A	N/A	3.54E-06	0.0216	N/A	N/A	2.96E-06	0.0256
Bi production	N/A	N/A	N/A	N/A	3.25E-04	4.84	4.92E-06	0.0426
Total	**4.20E-05**	**1.42**	**1.36E-02**	**82.8**	**4.37E-03**	**65.1**	**8.73E-03**	**75.6**
MANUFACTURING								
Solder manufacturing	2.81E-05	0.951	2.90E-05	0.177	2.22E-05	0.331	2.91E-05	0.252
Post-industrial recycling	4.87E-05	1.65	6.12E-05	0.374	1.99E-05	0.297	6.10E-05	0.528
Total	7.68E-05	2.60	9.02E-05	0.551	4.21E-05	0.627	9.01E-05	0.780
USE/APPLICATION								
Reflow application	2.01E-03	68.1	1.91E-03	11.7	1.48E-03	22.0	1.92E-03	16.6
Total	**2.01E-03**	**68.1**	**1.91E-03**	**11.7**	**1.48E-03**	**22.0**	**1.92E-03**	**16.6**
END-OF-LIFE								
Landfill	6.49E-04	22.0	6.42E-04	3.92	6.50E-04	9.67	6.42E-04	5.56
Incineration	1.65E-04	5.60	1.63E-04	1.00	1.74E-04	2.59	1.63E-04	1.41
Demanufacturing	1.78E-07	0.0060	1.54E-07	0.0009	1.82E-07	0.003	1.55E-07	0.0013
Cu smelting	8.06E-06	0.273	7.15E-06	0.0437	N/A	N/A	7.17E-06	0.0621
Unregulated	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00
Total	**8.23E-04**	**27.9**	**8.13E-04**	**4.97**	**8.24E-04**	**12.3**	**8.12E-04**	**7.03**
GRAND TOTAL	**2.95E-03**	**100**	**1.64E-02**	**100**	**6.72E-03**	**100**	**1.16E-02**	**100**

*The impact scores are in units of cubic meters (m^3) of landfill space/1,000 cc of solder applied to a printed wiring board.
N/A=not applicable

Of the four solder paste alloys, EOL processes contribute 5 to 28 percent of total landfill space use impacts, with the majority coming from the landfill process group itself. This process group contributes from 4 (for SAC) to 22 (for SnPb) percent of the total impacts, depending on the alloy, but the actual scores from the landfill process group for each alloy are essentially the same. Incineration, which produces ash that is landfilled, is the next greatest EOL contributor at 1 to 5.6 percent. Copper smelting also yields ash that requires a small amount of landfill space. The alloys that are sent to copper smelting have a small proportion of their impact scores from copper smelting, and an even smaller proportion from demanufacturing. Due to its high bismuth content, the BSA alloy is assumed to bypass the copper smelting process and go directly to landfilling and incineration from demanufacturing; therefore, there is no contribution from copper smelting for BSA, but it has a larger contribution from demanufacturing than the other alloys.

For the landfill space impact category, there are no negative impacts from incineration as there are with other impact categories. (Negative impacts arise from an energy credit for natural gas used in incineration with energy recovery). This is because the incineration process itself generates more landfilled waste than would be given credit from the natural gas savings from incineration with energy recovery. No landfill space use impacts are shown for unregulated disposal, as this process does not include disposal in a regulated landfill.

Landfill space use impacts from manufacturing are small compared to the upstream, use/application, and EOL life-cycle stages; these impacts are driven by both solder manufacturing and post-industrial recycling. For SnPb, SAC, and SABC, the post-industrial recycling impacts are greater than those from solder manufacturing (e.g., SAC post-industrial recycling is 6.12×10^{-5} m^3 per functional unit, while SAC solder manufacturing is 2.90×10^{-5} m^3/functional unit). For BSA, on the other hand, post-industrial recycling contributes less. The distribution of impacts in the manufacturing life-cycle stage is influenced by a combination of several factors including: landfilled waste generated during the post-industrial recycling process is greater than the solder manufacturing process, where much of the waste is sent to recycling; different melting points of the alloys, which affects the amount of energy used to melt the alloys and, therefore, the amount of waste from energy production; and varied secondary alloy content among the alloys.

Top Contributors to Landfill Space Use Impacts (Paste Solder)

Table 3-24 presents the specific materials or flows contributing greater than or equal to 1 percent of landfill space use impacts by solder paste. Slag from silver production is the top contributor for the three lead-free alloys that all contain silver in varying amounts. Landfilled slag from silver production contributes from 57 to 78 percent of the total landfill impact scores depending on the alloy. Sludge from silver production also contributes 4 to 6 percent to total impacts depending on the alloy. For the SnPb alloy, which does not contain silver in its composition, the top contributor at 65 percent is sludge from the U.S. electric grid which supplies electricity to the reflow application process in the use/application life-cycle stage. For the silver-containing alloys (e.g., the three lead-free alternatives), sludge from electricity supplied to the use/application stage is the second greatest contributor (10 to 20 percent of total impacts).

Landfilling of the alloy on a PWB at EOL is the next greatest contributor for each alloy, contributing from 4 to 24 percent of total impacts. As noted in the process group discussion above, the actual impact scores from this flow are essentially the same for each alloy. Smaller contributors include metals in ash from incineration sent to landfills (contributing 1 to 4 percent), and in the case of BSA, sludge from bismuth production (contributing approximately 4.6 percent to the BSA landfill impacts).

Table 3-24. Top contributors to landfill space use impacts (paste solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	Use/application	Electricity generation	Sludge (hazardous waste)	64.8
	End-of-life	Landfilling (SnPb)	Sn-Pb solder to landfill	23.5
	End-of-life	Solder incineration (SnPb)	Tin in ash to landfill	4.45
	End-of-life	Solder incineration (SnPb)	Lead in ash to landfill	1.67
	Upstream	Lead production	Sludge (hazardous waste)	1.16
SAC	Upstream	Silver production	Slag (hazardous waste)	77.8
	Use/application	Electricity generation	Sludge (hazardous waste)	10.4
	Upstream	Silver production	Sludge (hazardous waste)	5.72
	End-of-life	Landfilling (SAC)	SAC solder to landfill	3.97
BSA	Upstream	Silver production	Slag (hazardous waste)	57.1
	Use/application	Electricity generation	Sludge (hazardous waste)	20.0
	End-of-life	Landfilling (BSA)	BSA solder to landfill	9.86
	Upstream	Bismuth production	Sludge (hazardous waste)	4.55
	Upstream	Silver production	Sludge (hazardous waste)	4.20
	End-of-life	Solder incineration (BSA)	Bismuth in ash to landfill	1.29
	End-of-life	Solder incineration (BSA)	Tin in ash to landfill	1.27
SABC	Upstream	Silver production	Slag (hazardous waste)	71.3
	Use/application	Electricity generation	Sludge (hazardous waste)	14.9
	End-of-life	Landfillling (SABC)	SABC solder to landfill	5.65
	Upstream	Silver production	Sludge (hazardous waste)	5.24
	End-of-life	Solder incineration (SABC)	Tin in ash to landfill	1.38

3.2.3.3 Bar solder results

Total Landfill Space Use Impacts by Life-Cycle Stage (Bar Solder)

Table 3-25 presents the solder paste results for landfill space use impacts by life-cycle stage, based on the impact assessment methodology presented above. This impact category includes both hazardous and non-hazardous waste landfills. The table lists the impact scores per functional unit, as well as the percent contribution of each life-cycle stage to the total impacts for each alloy. Figure 3-9 presents the results in a stacked bar chart.

Table 3-25. Landfill space use impacts by life-cycle stage (bar solder)

Life-cycle stage	**SnPb**		**SAC**		**SnCu**	
	Score*	%	Score*	%	Score*	%
Upstream	3.79E-05	2.83	2.01E-02	94.0	1.40E-05	1.05
Manufacturing	1.07E-04	8.02	9.34E-05	0.436	1.26E-04	9.45
Use/application	2.87E-04	21.5	2.90E-04	1.36	2.90E-04	21.7
End-of-life	9.05E-04	67.7	9.03E-04	4.22	9.04E-04	67.8
Total	**1.34E-03**	**100**	**2.14E-02**	**100**	**1.33E-03**	**100**

*The impact scores are in units of m^3/1,000 cc of solder applied to a printed wiring board.

SAC solder paste has the greatest impact category indicator for landfill space use at 0.0214 m^3 per functional unit, followed by SnPb at 0.00134 m^3, and SnCu at

0.00133 m^3 per functional unit. The upstream life-cycle stage dominates the total landfill space score for SAC, accounting for 94 percent of the totals. On the other hand, SnPb and SnCu landfill space impacts are dominated by the EOL stage, each at approximately 68 percent of their total scores. The use/application stage is the second greatest contributor for SnPb and SnCu, followed by the manufacturing stage. The upstream stage contributes less then 3 percent for SnPb and SnCu. The EOL stage is the second greatest life-cycle stage for SAC (4 percent), followed by the use/application and manufacturing stages.

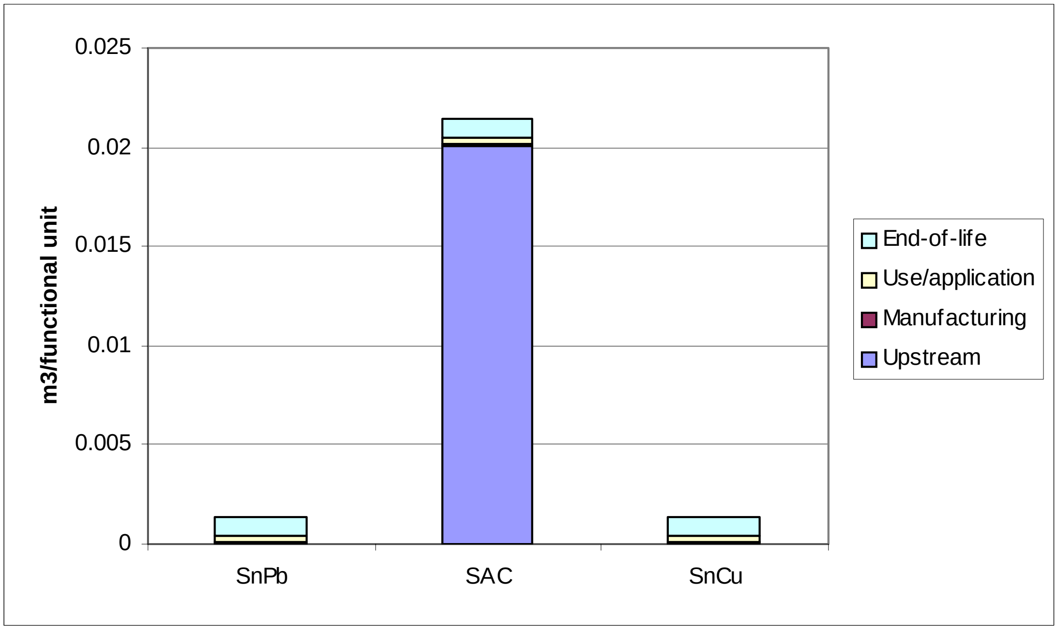


Figure 3-9. Bar Solder Total Life-Cycle Impacts: Landfill Space Use

Landfill Space Use Impacts by Process Group (Bar Solder)

Table 3-26 lists the landfill space use impacts of each of the process groups in the life-cycle of a solder paste. Landfill space use impacts are driven by the upstream processes for SAC that alone exceeds the total impacts from SnPb and SnCu. The silver production process contributes 94 percent of the total life-cycle landfill space use impacts. As stated under the paste solder results, this is of interest because the percent composition of silver is relatively small (3.9 percent), suggesting that the silver production process generates more landfilled waste per unit of metal produced than the other metals. For the SnPb and SnCu alloys, the upstream processes contribute only about 1 and 3 percent, respectively, to the total impacts, while it is the landfilling of process group (e.g., landfilling and associated diesel fuel production) that contributes the most to total impacts.

Table 3-26. Landfill space use impacts by life-cycle stage and process group (bar solder)

Life-cycle stage	**SnPb**		**SAC**		**SnCu**	
Process group	Score*	%	Score*	%	Score*	%
UPSTREAM						
Sn production	5.01E-06	0.375	1.06E-05	0.0496	8.19E-06	0.614
Pb production	3.29E-05	2.46	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	2.01E-02	93.9	N/A	N/A
Cu production	N/A	N/A	5.91E-06	0.0276	5.80E-06	0.434
Total	**3.79E-05**	**2.83**	**2.01E-02**	**94.0**	**1.40E-05**	**1.05**
MANUFACTURING						
Solder manufacturing	2.52E-05	1.89	5.63E-05	0.263	6.26E-05	4.69
Post-industrial recycling	8.20E-05	6.13	3.70E-05	0.173	6.35E-05	4.76
Total	**1.07E-04**	**8.02**	**9.34E-05**	**0.436**	**1.26E-04**	**9.45**
USE/APPLICATION						
Solder application	2.87E-04	21.5	2.90E-04	1.36	2.90E-04	21.7
Total	**2.87E-04**	**21.5**	**2.90E-04**	**1.36**	**2.90E-04**	**21.7**
END-OF-LIFE						
Landfill	7.22E-04	54.0	7.21E-04	3.37	7.21E-04	54.1
Incineration	1.74E-04	13.0	1.74E-04	0.812	1.75E-04	13.1
Demanufacturing	1.98E-07	0.0148	1.73E-07	0.0008	1.72E-07	0.0129
Cu smelting	8.95E-06	0.670	8.03E-06	0.0375	7.97E-06	0.597
Unregulated	0.00E+00	0.0000	0.00E+00	0.0000	0.00E+00	0.0000
Total	**9.05E-04**	**67.7**	**9.03E-04**	**4.22**	**9.04E-04**	**67.8**
GRAND TOTAL	**1.34E-03**	**100**	**2.14E-02**	**100**	**1.33E-03**	**100**

*The impact scores are in units of m^3/1,000 cc of solder applied to a printed wiring board.

N/A=not applicable

Of the three bar solder alloys, EOL processes contribute 4 to 68 percent of total landfill space use impacts, with the majority coming from the landfill process group itself. This process group contributes from 3 (for SAC) to 54 (for SnPb) percent of the total impacts, depending on the alloy, but the actual scores from the landfill process group for each alloy are essentially the same. As with the paste results, incineration, which produces ash that is landfilled, is the next greatest EOL contributor (1 to 13 percent of total impacts). Copper smelting also yields ash that requires a small amount of landfill space, thus, the alloys that are sent to copper smelting have a small proportion of their impact scores from copper smelting, and an even smaller proportion from demanufacturing.

For the landfill space impact category, there are no negative impacts from incineration as there are with other impact categories. (Negative impacts arise from an energy credit for natural gas used in incineration with energy recovery). This is because the incineration process itself generates more landfilled waste than would be given credit from the natural gas savings from incineration with energy recovery. No landfill space use impacts are shown for unregulated disposal as this process does not include disposal in a regulated landfill.

Landfill space use impacts from manufacturing are small compared to the upstream, use/application, and EOL life-cycle stages; these impacts are driven more or less by either solder manufacturing and post-industrial recycling, depending on the alloy and, particularly the amount of recycled versus virgin material used in manufacturing (discussed in earlier sections).

Top Contributors to Landfill Space Use Impacts (Bar Solder)

Table 3-27 presents the specific materials or flows contributing greater than or equal to 1 percent of landfill space use impacts by solder paste. For SnPb and SnCu, the solder on the PWB going to landfill is the top contributor to landfill space use (each is 54 percent of total impacts). For SAC, slag from silver production is the top contributor (87 percent of the total landfill impact score). Sludge from silver production also contributes 6 percent to total impacts depending on the alloy. For SnPb and SnCu, which do not contain silver, the second top contributor (at 21 percent) is sludge from the U.S. electric grid that supplies electricity to the wave application process in the use/application life-cycle stage. For SAC, sludge from electricity supplied to the use/application stage contributes only 1 percent of total impacts since slag and sludge from silver production dominate SAC's impacts.

Table 3-27. Top contributors to landfill space use impacts (bar solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	End-of-life	Landfilling (SnPb)	SnPb solder on PWB to landfill	53.7
	Use/application	Electricity generation	Sludge (hazardous waste)	21.1
	End-of-life	Solder incineration (SnPb)	Tin in ash to landfill	9.63
	End-of-life	Solder incineration (SnPb)	Lead in ash to landfill	3.62
	Manufacturing	Heavy fuel oil (#6) for post-industrial recycling	Sludge (hazardous waste)	3.37
	Upstream	Lead prodution	Sludge (hazardous waste)	2.12
	Manufacturing	Electricity generation for post-industrial recycling	Sludge (hazardous waste)	1.60
SAC	Upstream	Silver production	Slag (hazardous waste)	87.2
	Upstream	Silver production	Sludge (hazardous waste)	6.41
	End-of-life	Landfilling	SAC solder on PWB to landfill	3.36
	Use/application	Electricity generation	Sludge (hazardous waste)	1.34
SnCu	End-of-life	Landfilling	SnCu solder on PWB to landfill	53.8
	Use/application	Electricity generation	Sludge (hazardous waste)	21.4
	End-of-life	Incineration	Tin in ash to landfill	13.2
	Manufacturing	Heavy fuel oil (#6) production for post-industrial recycling	Sludge (hazardous waste)	3.19
	Manufacturing	LPG production for solder manufacturing	Slags and ash (hazardous waste)	2.26
	Manufacturing	Natural gas production for solder manufacturing	Sludge (hazardous waste)	1.19

3.2.3.4 Limitations and uncertainties

Landfill use pertains to the use of suitable and designated landfill space as a natural resource where the specified type of waste (solid or hazardous) is accepted. Landfill use impacts are characterized from solid or hazardous waste outputs with a disposition of landfill. Impact characterization is based on the volume of waste determined from the inventory mass amount of waste and materials density of each specific waste.

A limitation in the impact characterization method is that it only addresses the *volume* of landfill space used and not the type of materials in the landfilled waste. Toxic materials that are landfilled, and potentially leach from the landfill, are captured in other impact categories (e.g., public health and aquatic ecotoxicity impact categories). In addition, this impact category does not distinguish between hazardous and non-hazardous landfill space, and does not include radioactive waste landfill space. The radioactive waste landfill space would be directly proportional to the amount of electricity consumed in the life-cycle across all alloy alternatives and, as a boundary-setting decision, it was excluded from the scope in the goals and scoping phase of this LCA.

Limitations and uncertainties in the LCI data for top contributors to landfill space impacts also contribute to overall LCIA limitations and uncertainties. SnPb paste and bar impacts, as well as SnCu bar impacts, are driven by the use/application and EOL life-cycle stages, while the silver-bearing alloys (both paste and bar) are driven by silver production in the upstream life-cycle stage, and to a lesser degree, use/application and EOL. The major source of uncertainty in silver-bearing alternative alloys is the secondary data set used for silver production. As discussed in Section 3.2.1.4, although this process is considered of “good” quality per GaBi, an alternate analysis using another silver data set was conducted because life-cycle impacts in this and several other impact categories were largely being driven by the inventory for silver production (see Section 3.3).

The second greatest contributor to lead-free paste impact scores, and the greatest contributor to SnPb paste, is electricity generation from the reflow application of solder. Uncertainties in these data arise from the fact that (1) an average value from limited data representing high and low electricity consumption values was used for reflow electricity consumption, and (2) electricity production data are from a secondary source. A sensitivity analysis addressing the former source of uncertainty is presented in Section 3.3, but the latter is not considered large enough to warrant any further analysis.

Primary uncertainty in the EOL scores is related to the assumptions about the disposition of waste electronics. For example, we assumed that 72 percent of waste electronics is landfilled, based on the percent of waste electronics destined for recycling and the distribution of U.S. municipal solid waste between landfilling and incineration (EPA, 2002). The assumption about the percent of electronic waste currently being recycled is the best available information from EPA (described in Chapter 2); however, determining the fraction of that waste being diverted to unregulated recycling or the actual amount of electronics that are destined for landfills or other dispositions remains difficult.

Another source of uncertainty in EOL impacts is due to the fact that the volume of solder metals in incinerator ash was estimated based on the scientific literature for metals partitioning from incineration processes (see Chapter 2). These estimates were done specifically for this analysis and are not expected to be a large source of uncertainty. Uncertainty remains, however, because the data were for incineration of municipal waste, only a portion of which contained waste electronics. These data were compared against data measured from the incineration of selected computer equipment and were found to be comparable.

Finally, another limitation as it pertains to the disposal of waste electronics themselves (and not the disposal of waste from the extraction of fuels used to process waste electronics, for example) is that the EOL analysis only evaluates metal outputs from PWBs and waste electronics. This allows the analysis to focus on the metal alloys themselves, but does not include by-product outputs that might occur during EOL processes (e.g., volume of waste *PWBs* that are landfilled). If a separate analysis of EOL were done, and the actual outputs from the entire process of disposing or recycling waste electronics were considered, the results might be different.

3.2.4 Global Warming Impacts

3.2.4.1 Characterization

The build up of carbon dioxide (CO_2), and other greenhouse gases, in the atmosphere may generate a "greenhouse effect" of rising temperature and climate change. GWP refers to the warming, relative to CO_2, that chemicals contribute to this effect by trapping the Earth's heat. The impact scores for the effects of global warming and climate change are calculated using the mass of a global warming gas released to air, modified by a GWP equivalency factor. The GWP equivalency factor is an estimate of a chemical's atmospheric lifetime and radiative forcing that may contribute to global climate change compared to the reference chemical CO_2; therefore, GWPs are in units of CO_2 equivalents. GWPs have been published for known global warming chemicals within differing time horizons. The LCIA methodology employed in the LFSP uses GWPs having effects in the 100-year time horizon. Although LCA does not necessarily include a temporal component of the inventory, impacts from releases during the life-cycle of solder are expected to be within the 100-year time frame. Appendix D presents a current list of GWPs as identified by the Intergovernmental Panel on Climate Change (IPCC, 2001). Global warming impact scores are calculated for any chemicals in the LFSP LCI that are found on the list. The equation to calculate the impact score for an individual chemical is as follows:

$$(IS_{GW})_i = (EF_{GWP} \ x \ Amt_{GG})_i$$

where:

IS_{GW}	equals the global warming impact score for greenhouse gas chemical *i* (kg CO_2 equivalents) per functional unit;
EF_{GWP}	equals the GWP equivalency factor for greenhouse gas chemical *i* (CO_2 equivalents, 100-year time horizon) (Appendix D); and
Amt_{GG}	equals the inventory amount of greenhouse gas chemical *i* released to air (kg) per functional unit.

3.2.4.2 Paste solder results

Total Global Warming Impacts by Life-Cycle Stage (Paste Solder)

Table 3-28 presents the solder paste results for global warming impacts by life-cycle stage, based on the impact assessment methodology. The table lists the global warming impact scores per functional unit for the life-cycle stages of each solder paste alloy, as well as the percent contribution of each life-cycle stage to the total impacts. Figure 3-10 presents the results in a stacked bar chart.

Table 3-28. Global warming impacts by life-cycle stage (paste solder)

Life-cycle stage	SnPb		SAC		BSA		SABC	
	Score*	%	Score*	%	Score*	%	Score*	%
Upstream	5.92E+01	7.24	1.60E+02	18.4	7.58E+01	12.0	1.33E+02	15.7
Manufacturing	8.58E+00	1.05	9.28E+00	1.06	5.21E+00	0.825	9.28E+00	1.09
Use/application	7.49E+02	91.6	7.03E+02	80.5	5.50E+02	87.2	7.06E+02	83.2
End-of-life	6.18E-01	0.0756	5.35E-01	0.0612	4.49E-02	0.0071	5.37E-01	0.0633
Total	**8.17E+02**	**100**	**8.73E+02**	**100**	**6.31E+02**	**100**	**8.49E+02**	**100**

*The impact scores are in units of CO_2-equivalents/1,000 cubic centimeters of solder applied to a printed wiring board.

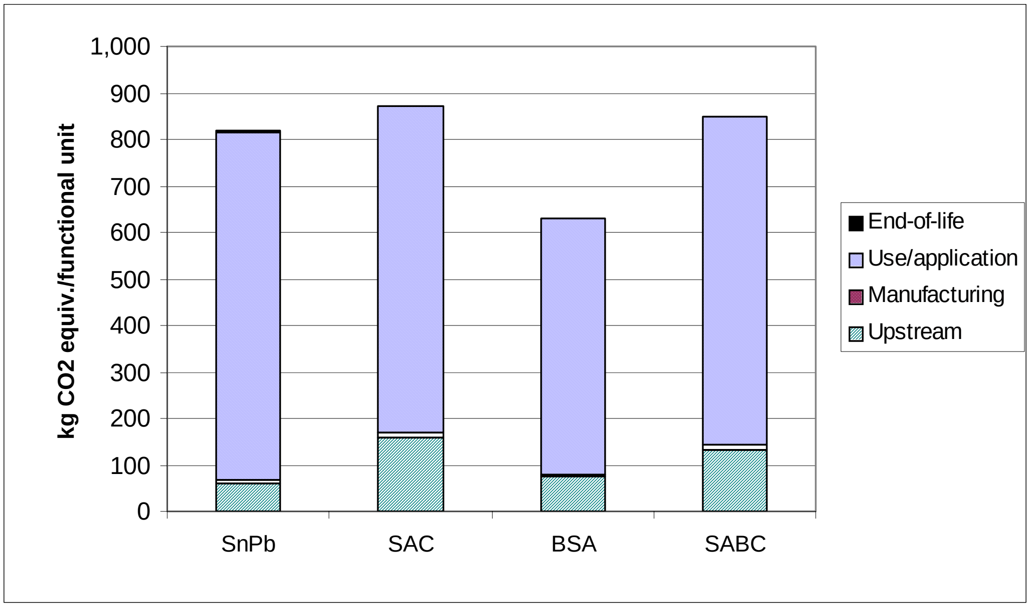


Figure 3-10. Solder Paste Total Life-Cycle Impacts: Global Warming

Global warming impacts follow the same pattern as energy use impacts. This is not unexpected as large amounts of electrical energy are used in the life-cycle of these alloys, and electricity generation produces considerable amounts of the global warming gas, CO_2. SAC solder paste has the greatest impact category indicator for global warming at 873 kg of CO_2-equivalents per functional unit, closely followed by SABC at 849 kg CO_2-equivalents, and SnPb at 817 kg CO_2-equivalents. BSA is the only solder with a substantially lower global warming impact (631 kg CO_2-equivalents per functional unit). This is due mostly to its lower melting temperature, and accordingly, its reduced energy requirements during reflow application (see discussion in Section 3.2.2.2). As shown in the table and figure, the use/application stage dominates global warming impacts for all of the solders, accounting for 81 to 92 percent of impacts depending on the alloy. Global warming impacts from Sn/Pb upstream processes (e.g., materials extraction and processing) are 59.2 kg of CO_2-equivalents/1,000 cc of solder compared to SAC for 160 kg CO_2-equivalents, BSA for 75.8 kg CO_2-equivalents, and SABC for 133 kg CO_2-equivalents. The upstream life-cycle stages contribute about 7 to18 percent of the total life-cycle impacts depending on the alloy. Solder manufacturing and EOL processes combined contribute less than 1.2 percent of the life-cycle global warming impacts of any of the solders.

Global Warming Impacts by Process Group (Paste Solder)

Table 3-29 lists the global warming impacts of each of the processes in the life-cycle of solder paste. Global warming impacts in the use/application stage are due entirely to electricity consumed in the solder reflow process. Conversely, upstream global warming impacts arise from the emissions associated with the extraction and processing of the various metals present in the alloys. The magnitude of global warming scores from silver processing approach those from tin processing in solders that contain both metals, even though the silver content of the alloys is much less than the tin content. For example, SAC is 95.5 percent tin and only 3.9 percent silver, yet SAC impacts from silver production (79.2 kg CO_2-equivalents) almost equal those from tin production (80.9 kg CO_2-equivalents). This is due to the relatively high energy intensity of silver extraction and processing compared to the other solder metals.

Table 3-29. Global warming impacts by life-cycle stage and process group (paste solder)

Life-cycle stage	**SnPb**		**SAC**		**BSA**		**SABC**	
Process group	Score*	%	Score*	%	Score*	%	Score*	%
UPSTREAM								
Sn production	5.53E+01	6.14	8.09E+01	8.43	4.14E+01	5.99	8.17E+01	8.73
Pb production	3.89E+00	0.432	N/A	N/A	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	7.92E+01	8.25	2.37E+01	3.42	5.10E+01	5.45
Cu production	N/A	N/A	7.80E-02	0.0081	N/A	N/A	6.53E-02	0.0070
Bi production	N/A	N/A	N/A	N/A	1.07E+01	1.54	1.62E-01	0.0173
Total	**5.92E+01**	**6.57**	**1.60E+02**	**16.7**	**7.58E+01**	**10.9**	**1.33E+02**	**14.2**
MANUFACTURING								
Solder manufacturing	2.92E+00	0.325	4.70E+00	0.490	2.89E+00	0.418	4.72E+00	0.504
Post-industrial recycling	5.66E+00	0.629	4.57E+00	0.477	2.32E+00	0.334	4.56E+00	0.487
Total	**8.58E+00**	**0.953**	**9.28E+00**	**0.966**	**5.21E+00**	**0.752**	**9.28E+00**	**0.992**
USE/APPLICATION								
Reflow application	8.32E+02	92.4	7.90E+02	82.3	6.11E+02	88.3	7.93E+02	84.8
Total	**8.32E+02**	**92.4**	**7.90E+02**	**82.3**	**6.11E+02**	**88.3**	**7.93E+02**	**84.8**
END-OF-LIFE								
Landfill	1.43E-02	0.0016	1.24E-02	0.0013	1.53E-02	0.0022	1.24E-02	0.0013
Incineration	-4.25E-02	-0.0047	-3.67E-02	-0.0038	-4.54E-02	-0.0066	-3.69E-02	-0.0039
Demanufacture	7.36E-02	0.0082	6.37E-02	0.0066	7.50E-02	0.0108	6.40E-02	0.0068
Cu smelting	5.72E-01	0.0636	4.95E-01	0.0516	N/A	N/A	4.97E-01	0.0531
Unregulated	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00
Total	**6.18E-01**	**0.0686**	**5.35E-01**	**0.0557**	**4.49E-02**	**0.0065**	**5.37E-01**	**0.0574**

Table 3-29. Global warming impacts by life-cycle stage and process group (paste solder)

Life-cycle stage	**SnPb**		**SAC**		**BSA**		**SABC**	
Process group	Score*	%	Score*	%	Score*	%	Score*	%
GRAND TOTAL	**9.00E+02**	**100**	**9.60E+02**	**100**	**6.92E+02**	**100**	**9.36E+02**	**100**

*The impact scores are in units of CO_2-equivalents/1,000 cubic centimeters of solder applied to a printed wiring board.
N/A=not applicable

Global warming impacts from the manufacturing life-cycle stage are small compared to the upstream and use/application life-cycle stages and are nearly evenly distributed between solder manufacturing and post-industrial recycling, with the exception of BSA. EOL processes contribute less than 0.07 percent of life-cycle global warming impacts for any of the solders, with the majority coming from smelting processes that recover copper and other valuable metals from waste electronics. Negative global warming impacts from incineration are due to the energy credit for incineration with energy recovery. No global warming impacts are shown for unregulated disposal as the inventory for this process does not include any global warming gas emissions or energy sources as inputs. Some energy is consumed, however, when waste PWBs are heated to recover solder and valuable components. The amount of energy consumed and the resulting global warming gases emitted in this process are not known, but are expected to be relatively small.

Top Contributors to Global Warming Impacts (Paste Solder)

Table 3-30 presents the specific materials or flows contributing at least 1 percent of the global warming impacts by solder. As expected from the results presented above, global warming gases generated from the production of electricity in the use/application stage are the top contributors to overall global warming impacts, with CO_2 being the single greatest contributor for all of the solders (ranging from 77 to 88 percent). CO_2 is primarily emitted from coal-fired power generation; coal is the primary fuel used to generate electricity in the U.S. electric grid. Electricity generated for the use/application stage also emits methane and nitrous oxide as top contributors to the overall global warming impacts. In addition to emissions from electricity generation in the use/application stage, other major contributors to global warming impacts include CO_2 from tin, silver, and bismuth production, depending on the alloy. The extraction and processing inventories are from secondary data sources that do not distinguish whether global warming gases are emitted from electric power plants producing electricity for the metals production processes or emitted directly during extraction and processing.

Table 3-30. Top contributors to global warming impacts (paste solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	Use/application	Electricity generation	Carbon dioxide	87.7
	Upstream	Tin production	Carbon dioxide	6.77
	Use/application	Electricity generation	Methane	2.84
	Use/application	Electricity generation	Nitrous oxide (laughing gas)	1.00
SAC	Use/application	Electricity generation	Carbon dioxide	77.1
	Upstream	Tin production	Carbon dioxide	9.27
	Upstream	Silver production	Carbon dioxide	8.59
	Use/application	Electricity generation	Methane	2.49
BSA	Use/application	Electricity generation	Carbon dioxide	83.4
	Upstream	Tin production	Carbon dioxide	6.57
	Upstream	Silver production	Carbon dioxide	3.55
	Use/application	Electricity generation	Methane	2.70
	Upstream	Bismuth production	Carbon dioxide	1.61
SABC	Use/application	Electricity generation	Carbon dioxide	79.6
	Upstream	Tin production	Carbon dioxide	9.62
	Upstream	Silver production	Carbon dioxide	5.69
	Use/application	Electricity generation	Methane	2.58

3.2.4.3 Bar solder results

Total Global Warming Impacts by Life-Cycle Stage (Bar Solder)

Table 3-31 presents the global warming impacts by life-cycle stage for bar solder based on the impact assessment methodology. The table lists the global warming impact scores per functional unit for the life-cycle stages of each bar solder alloy, as well as the percent contribution of each life-cycle stage to the total impacts. Figure 3-11 presents the results in a stacked bar chart.

Table 3-31. Global warming impacts by life-cycle stage (bar solder)

Life-cycle stage	SnPb		SAC		SnCu	
	Score*	%	Score*	%	Score*	%
Upstream	5.72E+01	30.5	2.31E+02	64.8	8.79E+01	40.8
Manufacturing	1.11E+01	5.92	5.19E+00	1.45	7.15E+00	3.32
Use/application	1.19E+02	63.2	1.20E+02	33.6	1.20E+02	55.6
End-of-life	6.89E-01	0.368	6.03E-01	0.169	5.99E-01	0.278
Total	**1.87E+02**	**100**	**3.57E+02**	**100**	**2.16E+02**	**100**

*The impact scores are in units of CO_2-equivalents/1,000 cubic centimeters of bar solder applied to a printed wiring board.

Global warming impacts for bar solder, much like solder paste, have a similar distribution as that for energy use impacts, due to the large amounts of electrical energy used over the life-cycle of these alloys. As mentioned before, electricity generation produces considerable amounts of the global warming gas, CO_2. SAC bar solder has the greatest impact category indicator for global warming at 357 kg of CO_2-equivalents per functional unit, followed by SnCu at 216 kg CO_2-equivalents, and SnPb at 187 kg CO_2-equivalents. Unlike the paste solders where the global warming impacts were dominated by the use/application stage, both the upstream and use/application stages contributed significantly to the global warming impacts for each of the bar solders. Global warming impacts from upstream processes (e.g., ME&P) for SAC are 231 kg of CO_2-equivalents/1,000 cc of solder compared to 87.9 kg CO_2-equivalents for SnCu and 57.2 kg CO_2-equivalents for SnPb. The upstream life-cycle stages contribute from 31 to 65 percent of the overall global warming impacts for any bar solder.

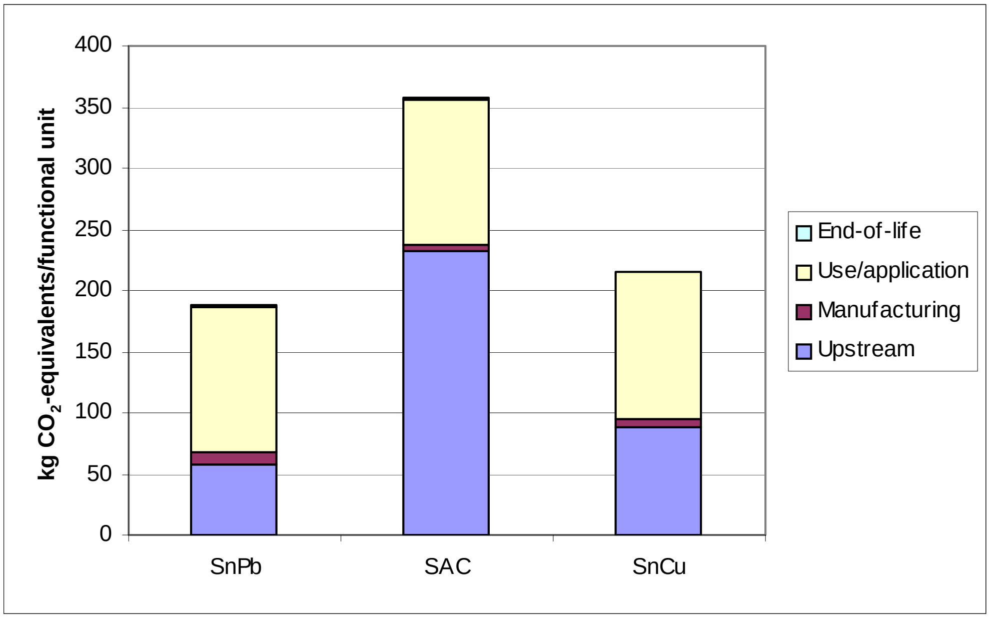


Figure 3-11. Bar Solder Total Life-Cycle Impacts: Global Warming

Though the impacts resulting from upstream processes varied greatly, global warming impacts resulting from the use/application stage were nearly identical for each of the solders, ranging from 119 to 120 kg CO_2-equivalents (see Chapter 2 for bar solder energy consumption details). Solder manufacturing and EOL processes combined contribute less than 6.3 percent of the life-cycle global warming impacts of any of the solders.

Global Warming Impacts by Process Group (Bar Solder)

Table 3-32 lists the global warming impacts resulting from each of the processes in the life-cycle of bar solder alloys. Upstream global warming impacts arise from the emissions associated with the extraction and processing of the various metals present in the alloys. The magnitude of global warming scores from silver processing (118 kg CO_2-equivalents) exceed those from tin processing (114 kg CO_2-equivalents) in the SAC alloy, even though the silver content of the alloys (0.6 percent) is much less than the tin content (95.5 percent). This is due to the relatively high energy intensity of silver extraction and processing compared to the other solder metals. Tin production accounts for the majority of the upstream impacts for the remaining solders which do not contain silver and have a tin content of at least 67 percent.

Table 3-32. Global warming impacts by life-cycle stage and process group (bar solder)

Life-cycle stage	**SnPb**		**SAC**		**SnCu**	
Process group	Score*	%	Score*	%	Score*	%
UPSTREAM						
Sn production	5.37E+01	28.6	1.14E+02	31.8	8.78E+01	40.7
Pb production	3.47E+00	1.85	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	1.18E+02	32.9	N/A	N/A
Cu production	N/A	N/A	1.30E-01	0.0365	1.28E-01	0.0593
Total	**5.72E+01**	**30.5**	**2.31E+02**	**64.8**	**8.79E+01**	**40.8**
MANUFACTURING						
Solder manufacturing	1.58E+00	0.840	2.42E+00	0.677	2.40E+00	1.11
Post-industrial recycling	9.53E+00	5.08	2.77E+00	0.775	4.75E+00	2.20
Total	**1.11E+01**	**5.92**	**5.19E+00**	**1.45**	**7.15E+00**	**3.32**
USE/APPLICATION						
Wave solder application	1.19E+02	63.2	1.20E+02	33.6	1.20E+02	55.6
Total	**1.19E+02**	**63.2**	**1.20E+02**	**33.6**	**1.20E+02**	**55.6**
END-OF-LIFE						
Landfill	1.59E-02	0.0085	1.39E-02	0.0013	1.38E-02	0.0064
Incineration	-4.47E-02	-0.0238	-3.91E-02	-0.0038	-3.88E-02	-0.0180
Demanufacturing	8.18E-02	0.0436	7.16E-02	0.0066	7.11E-02	0.0330
Cu smelting	6.36E-01	0.339	5.57E-01	0.0516	5.53E-01	0.256
Unregulated	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00
Total	**6.89E-01**	**0.37**	**6.03E-01**	**0.0557**	**5.99E-01**	**0.28**
GRAND TOTAL	**1.87E+02**	**100**	**3.57E+02**	**100**	**2.16E+02**	**100**

*The impact scores are in units of CO$_2$-equivalents/1,000 cubic centimeters of solder applied to a printed wiring board.
N/A=not applicable

Global warming impacts from the manufacturing life-cycle stage are small compared to the upstream and use/application life-cycle stages and are nearly evenly distributed between solder manufacturing and post-industrial recycling, with the exception of SnPb. Global warming impacts from the use/application stage are due entirely to the electricity consumed in the wave solder application process. These impacts are less dominant for bar solders than for the solder pastes, due to the reduced energy consumption per functional unit required by the wave process when compared to reflow assembly. For example, the global warming impacts for SnPb solder paste of 832 kg CO$_2$-equivalents greatly exceed the 119 kg CO$_2$-equivalents of global warming impacts for the wave application of SnPb bar solders.

EOL processes contribute less than 0.37 percent of life-cycle global warming impacts for any of the solders, with the majority coming from smelting processes that recover copper and other valuable metals from waste electronics. Negative global warming impacts from incineration are due to the energy credit for incineration with energy recovery. No global warming impacts are shown for unregulated disposal as the inventory for this process does not include any global warming gas emissions or energy sources as inputs. Some energy is consumed, however, when waste PWBs are heated to recover solder and valuable components. The amount of energy consumed, and the resulting global warming gases emitted in this process are not known, but are expected to be relatively small.

Top Contributors to Global Warming Impacts (Bar Solder)

Table 3-33 presents the specific materials or flows contributing at least 1 percent of the global warming impacts by solder. Consistent with the results presented above, global warming gases generated from the production of electricity in the use/application stage, along with those generated from the upstream extraction and processing of the metals, are the top contributors to overall global warming impacts. Carbon dioxide is the single greatest contributor for all of the solders, comprising at least 95 percent of the global warming releases. CO_2 is primarily emitted from coal-fired power generation (coal is the primary fuel used to generate electricity in the U.S. electric grid), but also is emitted during various upstream metal production processes. Methane is the only other listed contributor to global warming, resulting from the silver production process or from the generation of electricity used during the use/application stage. The extraction and processing inventories are from secondary data sources that do not distinguish whether global warming gases are emitted from electric power plants producing electricity for the metals production processes or emitted directly during extraction and processing.

Table 3-33. Top contributors to global warming impacts (bar solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	Use/application	Electricity generation	Carbon dioxide	60.5
	Upstream	Tin production	Carbon dioxide	28.6
	Manufacturing	Electricity generation for post-industrial recycling	Carbon dioxide	4.58
	Use/application	Electricity generation	Methane	1.96
	Upstream	Lead production	Carbon dioxide	1.74
SAC	Use/application	Electricity generation	Carbon dioxide	32.1
	Upstream	Tin production	Carbon dioxide	31.8
	Upstream	Silver production	Carbon dioxide	31.2
	Upstream	Silver production	Methane	1.61
	Use/application	Electricity generation	Methane	1.04
SnCu	Use/application	Electricity generation	Carbon dioxide	53.3
	Upstream	Tin production	Carbon dioxide	40.7
	Manufacturing	Electricity generation for post-industrial recycling	Carbon dioxide	1.88
	Use/application	Electricity generation	Methane	1.72

3.2.4.4 Limitations and uncertainties

Similar to the resource and energy impacts presented in Sections 3.2.1 and 3.2.2, respectively, the generation of electricity for the use/application stage is a major contributor to global warming impacts. As a result the same sources of uncertainty from the inventory apply: (1) reflow energy during application is based on a limited number of data points that cover a wide range, and (2) electricity production data are from secondary sources. Uncertainties in the reflow energy data are evaluated in a sensitivity analysis (see Section 3.3), but uncertainties in the electricity production data are not considered large enough to warrant any further analysis.

Limitations to this impact category also arise from aspects of the LCIA methodology. GWP refers to the warming that emissions of certain gases—by building up in the atmosphere and trapping the Earth's heat—may contribute. The LCIA methodology for global warming impacts uses published GWP equivalency factors having effects in the 100-year time horizon. These effects are expected to be far enough into the future that releases occurring throughout the life-cycle of solder on a PWB would be within the 100-year time frame.

The effects of the buildup of global warming gases in the atmosphere may still be the subject of scientific debate, but in 1995, the IPCC, representing the consensus of most climate scientists worldwide, concluded that "...the balance of evidence...suggests that there is a discernable human influence on global climate (IPCC, 1995)." As discussed above, other than the limitations and uncertainties inherent in predicting future effects, most of the limitations and uncertainties in the global warming results have to do with the LCI data on greenhouse gas emissions that occur primarily from electricity generation processes.

3.2.5 Stratospheric Ozone Depletion Impacts

3.2.5.1 Characterization

The stratospheric ozone layer filters out harmful ultraviolet radiation from the sun. Chemicals such as chlorofluorocarbons, if released to the atmosphere, may result in ozone-destroying chemical reactions. Stratospheric ozone depletion refers to the release of chemicals that may contribute to this effect. Impact scores are based on the identity and amount of ozone depleting chemicals released to air. Currently identified ozone depleting chemicals are those with ozone depletion potential (ODP), which measure the change in the ozone column in the equilibrium state of a substance compared to the reference chemical chlorofluorocarbon (CFC), CFC-11 (trichloroflurometane) (Heijungs *et al.*, 1992; CAAA, 1990). The list of ODPs that are used in this methodology are provided in Appendix D. The individual chemical impact score for stratospheric ozone depletion is based on the ODP and inventory amount of the chemical:

$$(IS_{OD})_i = (EF_{ODP} \times Amt_{ODC})_i$$

where:

IS_{OD}	equals the ozone depletion (OD) impact score for chemical *i* (kg CFC-11 equivalents) per functional unit;
EF_{ODP}	equals the ODP equivalency factor for chemical *i* (CFC-11 equivalents) (Appendix D); and
Amt_{ODC}	equals the amount of ozone depleting chemical *i* released to air (kg) per functional unit.

3.2.5.2 Paste solder results

Total Stratospheric Ozone Depletion Impacts by Life-Cycle Stage (Paste Solder)

Table 3-34 presents the solder paste results for stratospheric ozone depletion impacts by life-cycle stage, based on the impact assessment methodology presented above. The table lists the stratospheric ozone depletion impact scores per functional unit for the life-cycle stages of each solder paste alloy, as well as the percent contribution of each life-cycle stage to the total impacts. Figure 3-12 presents the results in a stacked bar chart.

Table 3-34. Stratospheric ozone depletion impacts by life-cycle stage (paste solder)

Life-cycle stage	SnPb		SAC		BSA		SABC	
	Score*	%	Score*	%	Score*	%	Score*	%
Upstream	4.85E-07	0.488	1.64E-05	14.9	7.58E-06	9.50	1.06E-05	10.1
Manufacturing	1.88E-06	1.89	2.28E-06	2.08	1.01E-06	1.26	2.28E-06	2.18
Use/application	9.69E-05	97.4	9.10E-05	82.8	7.12E-05	89.2	9.13E-05	87.5
End-of-life	2.47E-07	0.248	2.13E-07	0.194	4.83E-08	0.0605	2.14E-07	0.205
Total	**9.95E-05**	**100**	**1.10E-04**	**100**	**7.98E-05**	**100**	**1.04E-04**	**100**

*The impact scores are in units of kilograms CFC-11-equivalents/1,000 cubic centimeters of solder applied to a printed wiring board.

Following a pattern similar to energy and global warming impacts, the reflow of SAC solder has the greatest impact category indicator for stratospheric ozone depletion at 0.00011 kg of CFC-11-equivalents per functional unit, closely followed by SABC at 0.000104 kg of CFC-11-equivalents, and SnPb at 0.0000995 kg of CFC-11-equivalents. BSA results are substantially lower at 0.0000798 kg of CFC-11-equivalents per functional unit. It should be noted, that all of the materials contributing to this impact category are listed as Class I ozone depleting substances in Title VI of the 1990 Clean Air Act Amendments (CAAA), and, therefore, were phased-out of U.S. production as of January 1, 1996, with the exception of methyl bromide, which will be mainly phased-out by 2005. Production of these substances also was phased-out in other developed countries under the Montreal Protocol and its Amendments and Adjustments, but is permitted in developing countries until 2010 or 2015, depending on the substance. The uncertainties associated with having phased-out substances in the inventory and, therefore, in the LCIA results, are discussed further below.

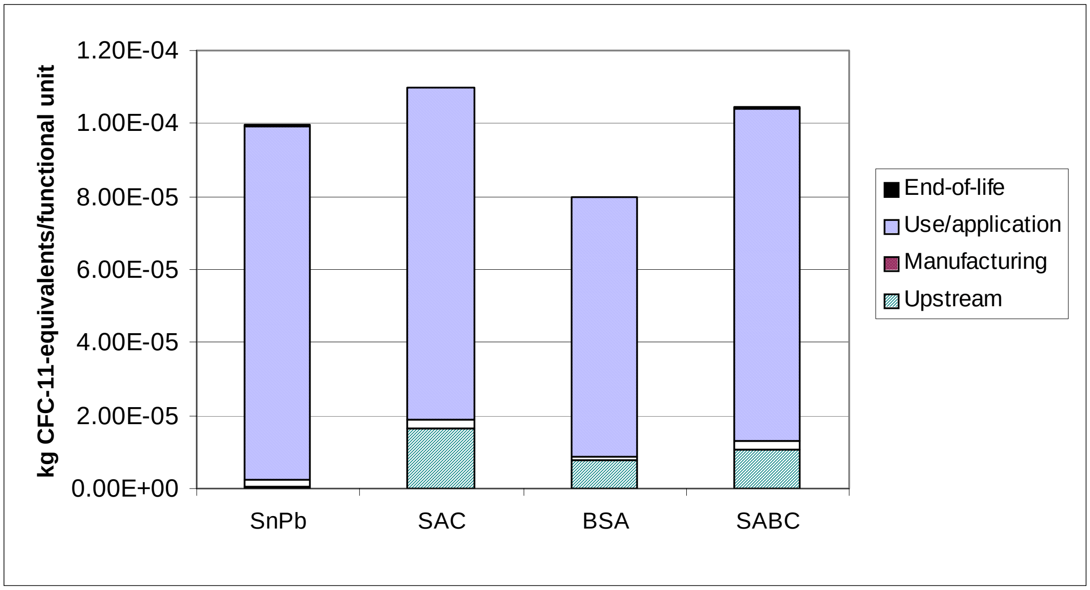


Figure 3-12. Solder Paste Total Life-Cycle Impacts: Stratospheric Ozone Depletion

As shown in the table and figure, the use/application stage dominates ozone depletion impacts for all of the solders, accounting for 83 to 97 percent of impacts depending on the alloy. The upstream processes contribute a larger portion of the total impacts for lead-free alternatives than they do for SnPb. In fact, for SAC and SABC, the scores for the upstream processes are high enough to cause the total impacts from these alternatives to exceed those from SnPb, despite the fact that SnPb use/application impacts are the greatest of all the alloys (6.1 percent higher than SABC, 6.5 percent higher than SAC). The upstream life-cycle stage for SnPb contributes less than 1 percent, while the upstream impacts for the three alternatives contribute 9 to 15 percent of the total life-cycle impacts. Solder manufacturing contributes 1 to 2 percent of the total stratospheric ozone depletion impacts, and EOL processes contribute less than 0.3 percent for all alloys.

Stratospheric Ozone Depletion Impacts by Process Group (Paste Solder)

Table 3-35 lists the stratospheric ozone depletion impacts of each of the processes in the life-cycle of a solder. Ozone depletion impacts in the use/application stage are due entirely to electricity consumed in the solder reflow process. Upstream ozone depletion impacts, on the other hand, arise from emissions from the extraction and processing of the various metals present in the alloys. It is noteworthy that there are no impacts from Sn production, despite the fact that tin is the largest or second largest metal component in each of the alloys. There is a small contribution to the impact category from lead processing for the SnPb alloy (4.85×10^{-7} kg CFC-11-equivalents per functional unit), with silver being the largest contributor for the lead-free alloys (e.g. 1.63×10^{-5} kg CFC-11-equivalents for SAC). Bismuth also is a significant contributor to the BSA upstream impacts (2.70×10^{-6} kg CFC-11-equivalents per functional unit).

Ozone depletion impacts from the manufacturing life-cycle stage are small compared to the use/application life-cycle stage. Manufacturing impacts are from energy consumed in solder manufacturing and post-industrial recycling. The distribution of the manufacturing impacts between these two processes is similar to that found for energy and global warming impacts, as discussed in Sections 3.2.2 and 3.2.4. EOL processes contribute less than 0.3 percent of total stratospheric ozone depletion impacts for any of the solders, with the majority coming from smelting processes used to recover copper and other valuable metals from waste electronics. The landfilling process group, which includes diesel fuel production, is the second greatest contributor to EOL impacts. There are no ozone depletion impacts from incineration or unregulated disposal as no ozone-depleting substances are emitted from these processes.

Table 3-35. Stratospheric ozone depletion impacts by life-cycle stage and process group (paste solder)

Life-cycle stage	**SnPb**		**SAC**		**BSA**		**SABC**	
Process group	Score*	%	Score*	%	Score*	%	Score*	%
UPSTREAM								
Sn production	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00
Pb production	4.85E-07	0.440	N/A	N/A	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	1.63E-05	13.5	4.88E-06	5.56	1.05E-05	9.09
Cu production	N/A	N/A	2.68E-08	0.0222	N/A	N/A	2.24E-08	0.0194
Bi production	N/A	N/A	N/A	N/A	2.70E-06	3.08	4.08E-08	0.0353
Total	**4.85E-07**	**0.440**	**1.64E-05**	**13.5**	**7.58E-06**	**8.64**	**1.06E-05**	**9.15**
MANUFACTURING								
Solder manufacturing	4.52E-07	0.410	6.75E-07	0.557	4.23E-07	0.482	6.77E-07	0.585
Post-industrial recycling	1.43E-06	1.29	1.61E-06	1.33	5.84E-07	0.666	1.60E-06	1.38
Total	**1.88E-06**	**1.71**	**2.28E-06**	**1.88**	**1.01E-06**	**1.15**	**2.28E-06**	**1.97**
USE/APPLICATION								
Reflow application	1.08E-04	97.6	1.02E-04	84.4	7.91E-05	90.2	1.03E-04	88.7
Total	**1.08E-04**	**97.6**	**1.02E-04**	**84.4**	**7.91E-05**	**90.2**	**1.03E-04**	**88.7**
END-OF-LIFE								
Landfill	3.61E-08	0.0327	3.12E-08	0.0258	3.86E-08	0.0440	3.13E-08	0.0271
Incineration	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00
Demanufacture	9.52E-09	0.0086	8.24E-09	0.0068	9.71E-09	0.0111	8.27E-09	0.0072
Cu smelting	2.01E-07	0.182	1.74E-07	0.144	N/A	N/A	1.75E-07	0.151
Unregulated	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00
Total	**2.47E-07**	**0.224**	**2.13E-07**	**0.176**	**4.83E-08**	**0.0550**	**2.14E-07**	**0.185**
GRAND TOTAL	**1.10E-04**	**100**	**1.21E-04**	**100**	**8.77E-05**	**100**	**1.16E-04**	**100**

*The impact scores are in units of kilograms CFC-11-equivalents/1,000 cubic centimeters of solder applied to a printed wiring board.

N/A=not applicable

Top Contributors to Stratospheric Ozone Depletion Impacts (Paste Solder)

Table 3-36 presents the specific materials or flows contributing at least 1 percent of ozone depletion impacts by solder. As expected from the results presented above, ozone-depleting substances emitted during the production of electricity in the use/application stage are the top contributors to overall ozone depletion impacts, with CFC-114 (dichlorotetrafluoroethane) and CFC-11(trichlorofluoromethane) being the two greatest contributors for each of the solders. Other top contributors include CFC-12 (dichlorodifluoromethane), Halon-1301, and CFC-13 (chlorotrifluoromethane), which are released from either electricity generation, silver production, or bismuth production. The extraction and processing inventories are from secondary data sources that do not distinguish whether the ozone-depleting substances are emitted from electric power used or directly emitted during extraction and processing.

Table 3-36. Top contributors to stratospheric ozone depletion impacts (paste solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	Use/application	Electricity generation	CFC-114	39.3
	Use/application	Electricity generation	CFC-11	38.4
	Use/application	Electricity generation	CFC-12	8.25
	Use/application	Electricity generation	Halon (1301)	6.30
	Use/application	Electricity generation	CFC-13	5.18
SAC	Use/application	Electricity generation	CFC-114	33.4
	Use/application	Electricity generation	CFC-11	32.6
	Use/application	Electricity generation	CFC-12	7.02
	Use/application	Electricity generation	Halon (1301)	5.36
	Upstream	Silver production	Halon (1301)	5.16
	Use/application	Electricity generation	CFC-13	4.41
	Upstream	Silver production	CFC-114	4.19
	Upstream	Silver production	CFC-11	4.09
BSA	Use/application	Electricity generation	CFC-114	36.0
	Upstream	Electricity generation	CFC-11	35.0
	Upstream	Electricity generation	CFC-12	7.55
	Use/application	Electricity generation	Halon (1301)	5.77
	Upstream	Electricity generation	CFC-13	4.74
	Upstream	Silver production	Halon (1301)	2.12
	Upstream	Silver production	CFC-114	1.72
	Upstream	Silver production	CFC-11	1.53
	Upstream	Bismuth production	CFC-114	1.10
SABC	Use/application	Electricity generation	CFC-114	35.3
	Use/application	Electricity generation	CFC-11	34.5
	Use/application	Electricity generation	CFC-12	7.41
	Use/application	Electricity generation	Halon (1301)	5.66
	Use/application	Electricity generation	CFC-13	4.65
	Upstream	Silver production	Halon (1301)	3.49
	Upstream	Silver production	CFC-114	2.84
	Upstream	Silver production	CFC-11	2.77

CFC-114 (dichlorotetrafluoroethane); CFC-11 (trichlorofluoromethane);
CFC-12 (dichlorodifluoromethane); CFC-13 (chlorotrifluoromethane)

While the top contributing flows to ozone depletion impacts result from three different processes—electricity, silver production, and bismuth production—there are a total of nine processes for all of the solder paste alloys within the life-cycle that emit ozone depleting substances (shown in the tables in Appendix D). These include electricity generation, selected fuel production (heavy fuel oil/#6, light fuel oil/#2, LPG, and diesel fuel), and selected ME&P (lead, silver, copper, and bismuth). The inventories for all these processes are from secondary data sources.

Table 3-37 lists the ozone-depleting substances released in the LFSP and their status under the U.S. CAAA and the Montreal Protocol. In addition to the five top contributors to total ozone depletion impacts shown in Table 3-36, two additional substances are relatively minor contributors to the results: methyl bromide and 1,1,1-trichloroethane. As shown in the table and discussed previously, all of these substances are Class I ozone depleting substances that were phased-out of production in the U.S. and developed countries as of 1996. An exception is methyl bromide, which is designated for phase-out in 2005, except for certain critical uses. All of these substances are still permitted in developing countries, but will be phased-out by 2010 or 2015, depending on the substance. The presence of phased-out substances in the inventories makes ozone depletion results highly uncertain, since it is unlikely they are still in use in areas covered by the geographic boundaries of the LFSP inventories. For example, most of the greatest ozone depletion impacts occur from U.S. electricity generation, yet it is unlikely U.S. power manufacturers continue to use these substances in routine operations. The implications of these uncertainties are discussed further below in Section 3.2.5.4.

Table 3-37. Ozone-depleting substances in the LFSP inventories

Substance	**Associated process(es)[a]**	**CAA[b]**	**Montreal Protocol[c]**
Methyl bromide	LPG production	Class I	Total phase out for all but certain critical uses by 2005 or 2015
Halon (1301)	All processes	Class I	Phased out by end of 1993 or 2010
Trichloroethane, 111- (methyl chloroform)	LPG production	Class I	Phased out by end of 1995 or 2015
CFC-13 (chlorotrifluoromethane)	All processes except LPG production	Class I	Phased out by end of 1995 or 2010
CFC-12 (dichlorodifluoromethane)	All processes except LPG production	Class I	Phased out by end of 1995 or 2010
CFC-114 (dichlorotetrafluoroethane)	All processes except LPG production	Class I	Phased out by end of 1995 or 2010
CFC-11 (trichlorofluoromethane)	All processes except LPG production	Class I	Phased out by end of 1995 or 2010

[a] Processes in LFSP that emit ozone-depleting substances are as follows: electricity generation, heavy fuel oil/#6, light fuel oil/#2, LPG, diesel fuel, lead, silver, copper, and bismuth.

[b] U.S. EPA regulations required the phase-out of Class I ozone-depleting substances, as listed in Title VI of the U.S. CAAA, as of 1996.

[c] Montreal Protocol phase outs for ozone-depleting substances differ for developed and developing countries; the earlier dates refer to developed countries and the later dates refer to developing countries.

3.2.5.3 Bar solder results

Total Stratospheric Ozone Depletion Impacts by Life-Cycle Stage (Bar Solder)

Table 3-38 presents the bar solder results for stratospheric ozone depletion impacts by life-cycle stage, based on the impact assessment methodology presented above. The table lists the stratospheric ozone depletion impact scores per functional unit for the life-cycle stages of each solder paste alloy, as well as the percent contribution of each life-cycle stage to the total impacts. Figure 3-13 presents the results in a stacked bar chart.

Table 3-38. Stratospheric ozone depletion impacts by life-cycle stage (bar solder)

Life-cycle stage	SnPb		SAC		SnCu	
	Score*	%	Score*	%	Score*	%
Upstream	4.33E-07	2.32	2.43E-05	58.8	4.40E-08	0.25
Manufacturing	2.63E-06	14.1	1.29E-06	3.11	1.98E-06	11.1
Use/application	1.53E-05	82.1	1.55E-05	37.5	1.55E-05	87.3
End-of-life	2.74E-07	1.47	2.40E-07	0.58	2.38E-07	1.34
Total	**1.87E-05**	**100**	**4.13E-05**	**100**	**1.78E-05**	**100**

*The impact scores are in units of kilograms CFC-11-equivalents/1,000 cubic centimeters of bar solder applied to a printed wiring board.

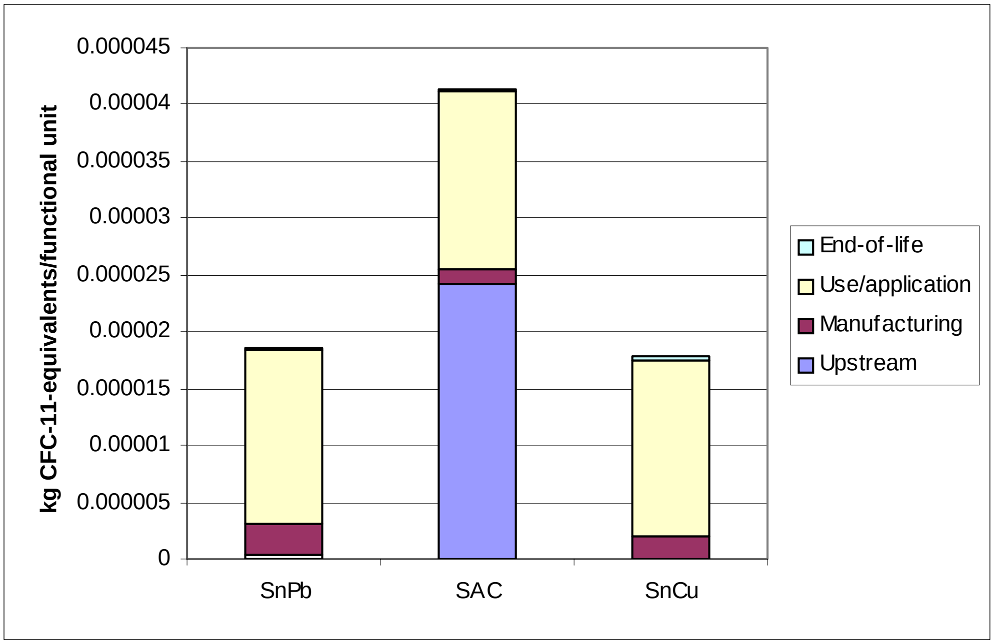


Figure 3-13. Bar Solder Total Life-Cycle Impacts: Stratospheric Ozone Depletion

SAC bar solder with 0.0000413 kg CFC-11 equivalents per functional unit had more than two times the number of ozone depletion impacts as the other bar solders. SnPb and SnCu follow with 0.0000187 and 0.0000178 kg CFC-11 equivalents per functional unit respectively. Unlike the solder pastes, this pattern differs slightly from the energy use and global warming impacts, where SnCu had slightly greater impacts than the baseline SnPb bar solder; however, it should again be noted that all of the materials contributing to this impact category are listed as Class I ozone depleting substances in Title VI of the 1990 CAAA and, therefore, were phased-out of U.S. production as of January 1, 1996, with the exception of methyl bromide, which will be mainly phased-out by 2005. Production of these substances also was phased-out in other developed countries under the Montreal Protocol and its Amendments and Adjustments, but is permitted in developing countries until 2010 or 2015, depending on the substance. The uncertainties associated with having phased-out substances in the inventory, and therefore, in the LCIA results, are further discussed below.

As shown in the table and figure, the ozone depletion impacts from the use/application stage dominate for the SnCu and SnPb solders, accounting for 87 and 82 percent respectively. Despite the use/application stage impact scores for the solders being virtually identical, ranging from 1.53 x 10^{-5} to 1.55 x10^{-5} kg CFC-11 equivalents per functional unit, the use/application stage accounted for just 38 percent of the overall ozone depletion impacts for the SAC alloy. The upstream stage impacts for SAC totaled 0.0000243 kg CFC-11 equivalents, or nearly 59 percent of the ozone depletion impact score. Upstream impacts for SnPb and SnCu accounted for less than 2.3 percent of the total impacts scores for these alloys. Manufacturing processes accounted for only 3.1 percent of the impacts for SAC, but ranged from 11 to 14 percent of the impacts of the non-silver containing solders. End-of-life impacts for all 3 bar solders contributed less than 1.5 percent of the overall impact scores.

Stratospheric Ozone Depletion Impacts by Process Group (Bar Solder)

Table 3-39 lists the stratospheric ozone depletion impacts of each of the processes in the life-cycle of a solder. Ozone depletion impacts in the use/application stage are due entirely to electricity consumed in the solder wave process. Upstream ozone depletion impacts, on the other hand, arise from emissions from the extraction and processing of the various metals present in the alloys. It is noteworthy that there are no impacts from tin production, despite the fact that tin is the largest or second largest metal component in each of the alloys. There is a small contribution to the impact category from silver processing for the SnPb alloy (4.33 x 10^{-7} kg CFC-11-equivalents per functional unit), with silver being the largest contributor for SAC (e.g. 2.43 x 10^{-5} kg CFC-11-equivalents for SAC). Copper production makes a minimal contribution to the overall ozone depletion impact score.

Ozone depletion impacts from the manufacturing life-cycle stage are small compared to the use/application life-cycle stage, though they contribute more than 11 percent of the overall impact score for the non-silver alloys. Manufacturing impacts are from energy consumed in solder manufacturing and post-industrial recycling, with post-industrial recycling accounting for the majority of the impacts. The distribution of the manufacturing impacts between these two processes is similar to that found for energy and global warming impacts, discussed in Sections 3.2.2 and 3.2.4. EOL processes contribute less than 1.5 percent of total stratospheric ozone depletion impacts for any of the solders, with the majority coming from smelting processes used to recover copper and other valuable metals from waste electronics. The landfilling process group, which includes diesel fuel production, is the second greatest contributor to EOL impacts. There are no ozone depletion impacts from incineration or unregulated disposal as no ozone-depleting substances are emitted from these processes.

Table 3-39. Stratospheric ozone depletion impacts by life-cycle stage and process group (bar solder)

Life-cycle stage	**SnPb**		**SAC**		**SnCu**	
Process group	Score*	%	Score*	%	Score*	%
UPSTREAM						
Sn production	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00
Pb production	4.33E-07	2.32	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	2.43E-05	58.7	N/A	N/A
Cu production	N/A	N/A	4.48E-08	0.108	4.40E-08	0.247
Total	**4.33E-07**	**2.32**	**2.43E-05**	**58.8**	**4.40E-08**	**0.247**
MANUFACTURING						
Solder manufacturing	2.27E-07	1.21	3.14E-07	0.759	3.12E-07	1.75
Post-industrial recycling	2.40E-06	12.9	9.72E-07	2.35	1.674E-06	9.38
Total	**2.63E-06**	**14.1**	**1.29E-06**	**3.11**	**1.98E-06**	**11.1**
USE/APPLICATION						
Reflow application	1.53E-05	82.1	1.55E-05	37.5	1.55E-05	87.3
Total	**1.53E-05**	**82.1**	**1.55E-05**	**37.5**	**1.55E-05**	**87.3**
END-OF-LIFE						
Landfill	4.01E-08	0.215	3.51E-08	0.0848	3.48E-08	0.196
Incineration	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00
Demanufacturing	1.06E-08	0.057	9.26E-09	0.0224	9.20E-09	0.0517
Cu smelting	2.23E-07	1.20	1.95E-07	0.473	1.94E-07	1.09
Unregulated	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00
Total	**2.74E-07**	**1.47**	**2.40E-07**	**0.580**	**2.38E-07**	**1.34**
GRAND TOTAL	**1.87E-05**	**100**	**4.13E-05**	**100**	**1.78E-05**	**100**

*The impact scores are in units of kilograms CFC-11-equivalents/1,000 cubic centimeters of bar solder applied to a printed wiring board.

N/A=not applicable

Top Contributors to Stratospheric Ozone Depletion Impacts (Bar Solder)

Table 3-40 presents the specific materials or flows contributing at least 1 percent of ozone depletion impacts by solder. As expected from the results presented above, ozone-depleting substances emitted during the production of electricity in the use/application stage are the top contributors to overall ozone depletion impacts, with CFC-114 and CFC-11 being the two greatest contributors for each of the solders. Other top contributors include CFC-12, Halon-1301, and CFC-13, which are released from electricity generation, silver production, or the production of heavy fuel oil used in post-industrial recycling. The extraction and processing inventories are from secondary data sources that do not distinguish whether the ozone-depleting substances are emitted from electric power used or directly emitted during extraction and processing.

Table 3-40. Top contributors to stratospheric ozone depletion impacts (bar solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	Use/application	Electricity generation	CFC-114	33.1
	Use/application	Electricity generation	CFC-11	32.4
	Use/application	Electricity generation	CFC-12	6.96
	Manufacturing	Heavy fuel oil (#6) production, post-industrial recycling	Halon (1301)	5.98
	Use/application	Electricity generation	Halon (1301)	5.31
	Use/application	Electricity generation	CFC-13	4.37
	Manufacturing	Electricity generation, post-industrial recycling	CFC-114	2.51
	Manufacturing	Electricity generation, post-industrial recycling	CFC-11	2.45
SAC	Upstream	Silver production	Halon (1301)	20.3
	Upstream	Silver production	CFC-114	16.5
	Upstream	Silver production	CFC-11	16.1
	Use/application	Electricity generation	CFC-114	15.1
	Use/application	Electricity generation	CFC-11	14.8
	Upstream	Silver production	CFC-12	3.47
	Use/application	Electricity generation	CFC-12	3.18
	Use/application	Electricity generation	Halon (1301)	2.43
	Upstream	Silver production	CFC-13	2.18
	Use/application	Electricity generation	CFC-13	2.00
	Manufacturing	Heavy fuel oil (#6) production, post-industrial recycling	Halon (1301)	1.49
SnCu	Use/application	Electricity generation	CFC-114	35.2
	Use/application	Electricity generation	CFC-11	34.4
	Use/application	Electricity generation	CFC-12	7.39
	Manufacturing	Heavy fuel oil (#6) production, post-industrial recycling	Halon (1301)	5.94
	Use/application	Electricity generation	Halon (1301)	5.65
	Use/application	Electricity generation	CFC-13	4.64
	Manufacturing	Electricity generation, post-industrial recycling	CFC-114	1.24
	Manufacturing	Electricity generation, post-industrial recycling	CFC-11	1.22

While the top contributing flows to ozone depletion impacts result from three different processes—electricity, silver production, and heavy fuel oil production—there are a total of nine processes for all of the solder paste alloys within the life-cycle that emit ozone depleting substances (shown in the tables in Appendix D). These include electricity generation, selected fuel production (heavy fuel oil/#6, light fuel oil/#2, LPG, and diesel fuel), and selected ME&P (lead, silver, copper, and bismuth). The inventories for all these processes are from secondary data sources.

In addition to the top contributing ozone depleting substances presented above, two other substances, methyl bromide and trichloroethane- 1,1,1, also are emitted from bar solder life-cycle processes. All of these substances either have been designated or already have been phased out in the U.S. Please refer to the paste solder section above (Section 3.2.5.3) and for further discussion of this issue and the potential limitations and uncertainties.

3.2.5.4 Limitations and uncertainties

The major contributors to stratospheric ozone depletion impacts are from the generation of electricity for the use/application stage and from silver production. These contributors, therefore, are subject to the same sources of uncertainty in the use/application stage inventory: (1) reflow energy consumption during application/use is based on a limited number of data points that cover a wide range, and (2) electricity production data are from a secondary source. Uncertainties in the reflow energy data are the subject of a sensitivity analysis (see Section 3.3), but uncertainties in the electricity production data are considered relatively minor.

The silver inventory, which contributes significantly to the ozone depletion impact score for SAC, warrants discussion here. Uncertainties related to the silver inventory are described in Section 3.2.2.3, and have to do with the fact that two alternate silver inventories available to the LFSP vary significantly in the magnitude of flows from silver production. Section 3.2.2.3 concludes that although the GaBi data set used in this analysis is considered "good' by GaBi, there remains enough uncertainty to perform an additional analysis using the alternate inventory from the DEAM database. Results of the alternate analysis are presented in Section 3.3.

The principle difference between paste and bar solder are the manufacturing of the solder and the manner in which it is applied. For bar solder, the wave application data are expected to be representative of general wave operations of good quality. The remaining uncertainty, although expected to be small, is that the electricity production data used for the wave operations are derived from secondary data.

Perhaps the most significant source of uncertainty in the ozone depletion results is the presence of phased-out substances in the inventory. In order to better assess these uncertainties, Table 3-41 lists the geographic and temporal boundaries for the life-cycle inventories of the processes that emit ozone-depleting substances. As shown in the table, these processes contain data from developed countries and from dates that precede the phase-out dates; therefore, if it is assumed that these substances were indeed phased out as required, only methyl bromide would be included in the inventory.

Figure 3-14 presents ozone depletion impact results for solder paste if only methyl bromide were in the inventory. Methyl bromide emissions result from the production of LPG, which is used in post-industrial recycling (manufacturing life-cycle stage) and copper smelting (EOL life-cycle stage). The figure shows that only upstream and EOL life-cycle stages contribute to these results. This is in contrast to the results presented in Figure 3-12, which are based on the inventory using the phased-out substances.

Table 3-41. Geographic and temporal boundaries of inventories contributing to the ozone depletion results

Process	Geographic boundaries	Temporal boundaries
Electricity generation	United States	1995
Heavy fuel oil/#6	Germany	1994
Light fuel oil/#2	Germany	1994
LPG production	Mainly United States	1980-1993
Diesel fuel production	Germany	1994
Lead production	Germany	1995
Silver production	"Global" (Canada, Sweden)	1995
Copper production	Germany	1994-1996
Bismuth production	Germany	1994-1996

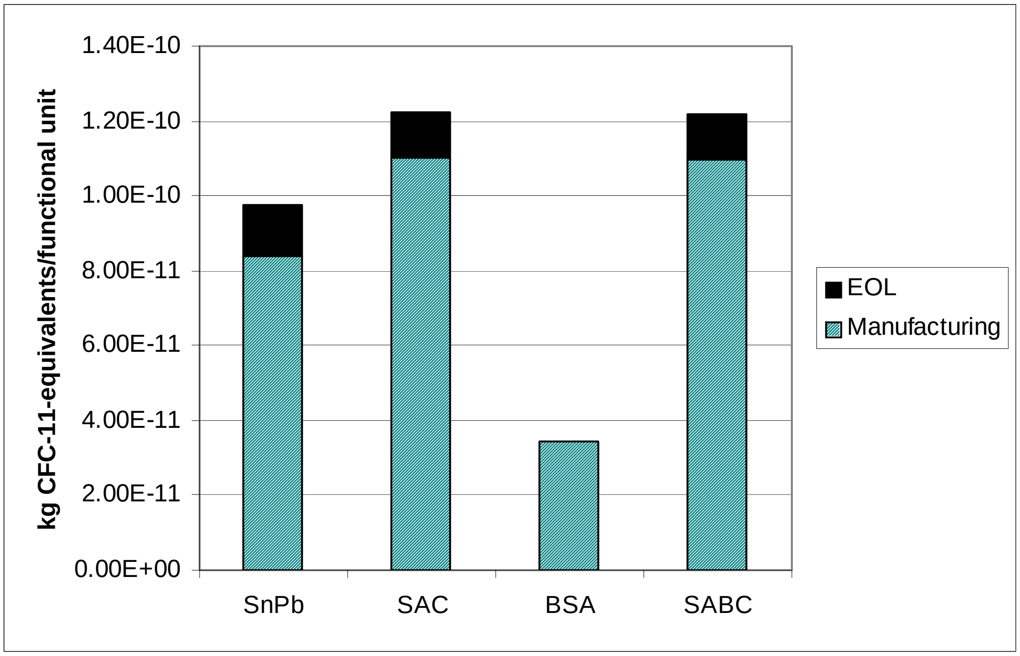


Figure 3-14. Ozone Depletion Impacts with Methyl Bromide Only (Paste Solder)

The results in Figure 3-14, compared to those presented in Figure 3-12 show that SAC still has the greatest impact score, followed by SABC. SnPb has the third greatest impact score, as shown in Figure 3-12. Adjustment of the inventory to exclude materials due to their expected phase-out has resulted in an even greater gap between BSA and their other solders. As expected, the total impact scores for stratospheric ozone depletion are much less (ranging from about 3.43×10^{-11} to 1.22×10^{-10} kg CFC-11- equivalents/functional unit) compared to the results in Figure 3-12, which range from 8.77×10^{-5} to 1.21×10^{-4} kg CFC-11-equivalents/functional unit; however, it should be noted that even these results are uncertain since the schedule for methyl bromide phase-out required a 25 percent reduction in 1999 and a 70 percent reduction in 2003.

Given the phase-out schedule, and the fact that many manufacturers have actively pursued alternatives for non-critical uses of methyl bromide, it is entirely possible that methyl bromide is no longer used in LPG production.

In conclusion, the major limitation to the ozone depletion results is that many of the flows contributing to ozone depletion impacts have been theoretically phased-out. Lending to the uncertainty is the fact that if the ozone-depleting substances have indeed been phased-out, any substitute materials have not been inventoried in this study.

3.2.6 Photochemical Smog Impacts

3.2.6.1 Characterization

Photochemical oxidants are produced in the atmosphere from sunlight reacting with hydrocarbons and nitrogen oxides. At higher concentrations they may cause or aggravate health problems, plant toxicity, and deterioration of certain materials. Photochemical oxidant creation potential (POCP) refers to the release of chemicals that contribute to this effect. The POCP is based on simulated trajectories of tropospheric ozone production both with and without volatile organic carbons (VOCs) present. The POCP is a measure of a specific chemical compared to the reference chemical ethene (Heijungs *et al.*, 1992). The list of chemicals with POCPs used in this methodology is presented in Appendix D. As shown in Table 3-42, photochemical smog impacts are based on partial equivalency because some chemicals cannot be converted into POCP equivalency factors. For example, nitrogen oxides do not have a POCP; however, VOCs are assumed to be the limiting factor, and if VOCs are present there is a potential impact. Impact scores are based on the identity and amount of chemicals with POCP equivalency factors released to the air and the chemical-specific equivalency factor:

$$(IS_{POCP})_i = (EF_{POCP} \times Amt_{POC})_i$$

where:

IS_{POCP}	equals the photochemical smog (POCP) impact score for chemical *i* (kg ethene equivalents) per functional unit;
EF_{POCP}	equals the POCP equivalency factor for chemical *i* (ethene equivalents) (Appendix D); and
Amt_{POC}	equals the amount of photochemical smog-creating oxidant *i* released to the air (kg) per functional unit.

3.2.6.2 Paste solder results

Total Photochemical Smog Impacts by Life-Cycle Stage (Paste Solder)

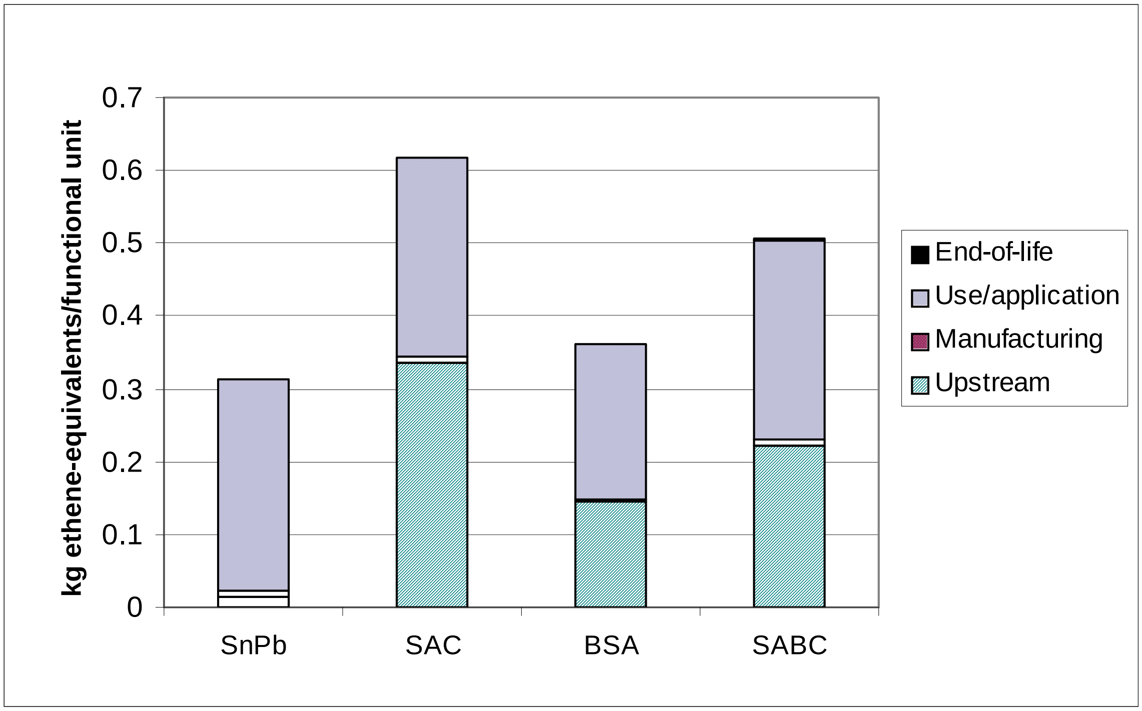
Table 3-42 presents the solder paste results for photochemical smog impacts by life-cycle stage based on the impact assessment methodology. The table lists the photochemical smog impact scores per functional unit for the life-cycle stages of each alloy, as well as the percent contribution of each life-cycle stage to the total impacts. Figure 3-15 shows the results in a stacked bar chart.

Table 3-42. Photochemical smog impacts by life-cycle stage (paste solder)

Life-cycle stage	SnPb		SAC		BSA		SABC	
	Score*	%	Score*	%	Score*	%	Score*	%
Upstream	1.56E-02	4.98	3.37E-01	54.5	1.44E-01	39.9	2.23E-01	44.2
Manufacturing	6.28E-03	2.00	7.38E-03	1.19	3.47E-03	0.961	7.38E-03	1.46
Use/application	2.91E-01	92.8	2.73E-01	44.2	2.14E-01	59.2	2.74E-01	54.3
End-of-life	6.34E-04	0.202	5.49E-04	0.0888	2.70E-05	0.0075	5.51E-04	0.109
Total	**3.13E-01**	**100**	**6.18E-01**	**100**	**3.61E-01**	**100**	**5.05E-01**	**100**

*The impact scores are in units of ethene-equivalents/1,000 cubic centimeters of solder applied to a printed wiring board.

Figure 3-15. Solder Paste Total Life-Cycle Impacts: Photochemical Smog



As shown in the table and figure, SAC solder has the greatest impact category indicator at 0.618 kg of ethene-equivalents/functional unit for photochemical smog, followed by SABC at 0.505 kg ethene-equivalents. BSA and SnPb results are substantially lower with photochemical smog impact indicators of 0.361 and 0.313 kg ethene-equivalents, respectively. Nearly 93 percent of the SnPb smog impacts are driven by the use/application stage, while the lead-free options are driven by both the upstream and use/application life-cycle stages. Solder paste manufacturing and EOL processes contribute very little to the overall smog impact scores for any of the alloys.

Photochemical Smog Impacts by Process Group (Paste Solder)

Table 3-43 lists the photochemical smog impact scores for each of the processes in the life-cycle of a solder paste. As with other impact categories, impacts from the use/application life-cycle stage are entirely from the solder reflow process group. For the lead-free alloys, smog impacts from upstream processes are due primarily to the silver production process, even though silver is only a small proportion of the alloy composition. For example, silver production contributes 25 to 49 percent of the total smog impacts for the lead-free solder alternatives while the percent composition of silver in those alloys range from 1 to 3.9 percent. For BSA, which is composed of 57 percent bismuth, only 11 percent of smog impacts are due to bismuth production.

Table 3-43. Photochemical smog impacts by life-cycle stage and process group (paste solder)

Life-cycle stage	**SnPb**		**SAC**		**BSA**		**SABC**	
Process group	Score*	%	Score*	%	Score*	%	Score*	%
UPSTREAM								
Sn production	1.02E-02	2.96	1.50E-02	2.30	7.67E-03	1.99	1.51E-02	2.80
Pb production	5.37E-03	1.55	N/A	N/A	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	3.22E-01	49.3	9.61E-02	25.0	2.07E-01	38.4
Cu production	N/A	N/A	4.27E-04	0.0655	N/A	N/A	3.57E-04	0.0663
Bi production	N/A	N/A	N/A	N/A	4.03E-02	10.5	6.09E-04	0.113
Total	**1.56E-02**	**4.51**	**3.37E-01**	**51.7**	**1.44E-01**	**37.4**	**2.23E-01**	**41.4**
MANUFACTURING								
Solder manufacturing	1.94E-03	0.560	2.50E-03	0.384	1.69E-03	0.440	2.51E-03	0.466
Post-industrial recycling	4.34E-03	1.26	4.88E-03	0.749	1.78E-03	0.461	4.87E-03	0.903
Total	**6.28E-03**	**1.82**	**7.38E-03**	**1.13**	**3.47E-03**	**0.901**	**7.38E-03**	**1.37**
USE/APPLICATION								
Reflow application	3.23E-01	93.5	3.07E-01	47.1	2.37E-01	61.7	3.08E-01	57.1
Total	**3.23E-01**	**93.5**	**3.07E-01**	**47.1**	**2.37E-01**	**61.7**	**3.08E-01**	**57.1**
END-OF-LIFE								
Landfill	1.20E-04	0.0348	1.05E-04	0.0162	1.29E-04	0.0335	1.06E-04	0.0196
Incineration	-1.23E-04	-0.0355	-1.07E-04	-0.0165	-1.31E-04	-0.0341	-1.08E-04	-0.0200
Demanufacturing	3.18E-05	0.0092	2.78E-05	0.0043	3.24E-05	0.0084	2.79E-05	0.0052
Cu smelting	6.75E-04	0.195	5.91E-04	0.0906	N/A	N/A	5.93E-04	0.110
Unregulated	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00
Total	**7.05E-04**	**0.204%**	**6.17E-04**	**0.0946**	**3.01E-05**	**0.0078**	**6.19E-04**	**0.115**
GRAND TOTAL	**3.46E-01**	**100%**	**6.52E-01**	**100**	**3.85E-01**	**100**	**5.39E-01**	**100**

*The impact scores are in units of ethene-equivalents/1,000 cubic centimeter of solder applied to a printed wiring board.

N/A=not applicable

Within the manufacturing life-cycle stage, the post-industrial recycling process is a greater contributor than solder manufacturing for all solder paste alloys except BSA. The distribution of the manufacturing impacts between these two processes is similar to those found for energy, and is discussed in Section 3.2.2; however, the manufacturing stage is a small contributor overall.

EOL processes contribute less than 0.3 percent of total photochemical smog impacts for any of the solders, with the majority coming from smelting processes used to recover copper and other valuable metals from waste electronics. The landfilling process group, which includes diesel fuel production, is the second greatest contributor to EOL impacts. Demanufacturing contributes less than 0.01 percent for each alloy, and incineration results in a credit based on the surplus energy generated during the incineration of electronics at EOL.

Top Contributors to Photochemical Smog Impacts (Paste Solder)

Table 3-44 presents the specific materials or flows contributing at least 1 percent of photochemical smog impacts by solder. As expected from the results above, all the top contributors are from either the use/application stage or the upstream life-cycle stage. Sulphur dioxide is the largest contributing individual flow and is emitted during either electricity production or silver production, depending on the alloy.

For SnPb, sulphur dioxide from the generation of electricity used to reflow solder contributes about 65 percent to the total smog impact score. Other flows from the use/application stage for electricity generation, such as unspecified non-methane volatile organic compounds (NMVOCs), carbon monoxide, xylene, ethane, and methane, all contribute at least 1 percent each to the total smog impact score for SnPb. Other flows for SnPb presented in the table include sulphur dioxide from tin production (3 percent) and sulphur dioxide from lead production (1 percent).

Sulphur dioxide resulting from the electricity used in both solder application and silver production also is the greatest contributor for the silver-containing alloys. The percent contribution from sulphur dioxide, from both electricity generation for the use/application stage and silver production combined, range from 66 percent to 79 percent for the lead-free solders. Others, including unspecified NMVOCs, carbon monoxide, xylene, and methane, contribute at least 1 percent each of the total impacts per alloy. These flows all result from the production of the metals required to manufacture the solder paste. The extraction and processing inventories are from secondary data sources that do not distinguish whether the smog-inducing substances are emitted from electric power used or directly released during extraction and processing.

Table 3-44. Top contributors to photochemical smog impacts (paste solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	Use/application	Electricity generation	Sulphur dioxide	65.1
	Use/application	Electricity generation	NMVOC (unspecified)	15.3
	Use/application	Electricity generation	Carbon monoxide	4.37
	Upstream	Tin production	Sulphur dioxide	3.08
	Use/application	Electricity generation	Xylene (dimethyl benzene)	2.47
	Use/application	Electricity generation	Methane	1.93
	Use/application	Electricity generation	Ethane	1.38
	Upstream	Lead production	Sulphur dioxide	1.27
SAC	Upstream	Silver production	Sulphur dioxide	47.9
	Use/application	Electricity generation	Sulphur dioxide	31.0
	Use/application	Electricity generation	NMVOC (unspecified)	7.28
	Upstream	Silver production	NMVOC (unspecified)	3.36
	Upstream	Tin production	Sulphur dioxide	2.29
	Use/application	Electricity generation	Carbon monoxide	2.08
	Use/application	Electricity generation	Xylene (dimethyl benzene)	1.17
BSA	Use/application	Electricity generation	Sulphur dioxide	41.5
	Upstream	Silver production	Sulphur dioxide	24.5
	Use/application	Electricity generation	NMVOC (unspecified)	9.75
	Upstream	Bismuth production	Sulphur dioxide	9.65
	Use/application	Electricity generation	Carbon monoxide	2.79
	Upstream	Tin production	Sulphur dioxide	2.00
	Upstream	Silver production	NMVOC (unspecified)	1.72
	Use/application	Electricity generation	Xylene (dimethyl benzene)	1.57
	Use/application	Electricity generation	Methane	1.23
	Upstream	Bismuth production	NMVOC (unspecified)	1.17
SABC	Use/application	Electricity generation	Sulphur dioxide	38.1
	Upstream	Silver production	Sulphur dioxide	37.7
	Use/application	Electricity generation	NMVOC (unspecified)	8.95
	Upstream	Tin production	Sulphur dioxide	2.82
	Upstream	Silver production	NMVOC (unspecified)	2.65
	Use/application	Electricity generation	Carbon monoxide	2.56
	Use/application	Electricity generation	Xylene (dimethyl benzene)	1.44
	Use/application	Electricity generation	Methane	1.13

3.2.6.3 Bar solder results

Total Photochemical Smog Impacts by Life-Cycle Stage (Bar Solder)

Table 3-45 presents the bar solder results for photochemical smog impacts by life-cycle stage, based on the impact assessment methodology presented above (Section 3.2.6.1). The table lists the photochemical smog impact scores per functional unit for the life-cycle stages of each alloy, as well as the percent contribution of each life-cycle stage to the total impacts. Figure 3-16 shows the results in a stacked bar chart.

Table 3-45. Photochemical smog impacts by life-cycle stage (bar solder)

Life-cycle stage	SnPb		SAC		SnCu	
	Score*	%	Score*	%	Score*	%
Upstream	1.47E-02	21.1	4.99E-01	90.6	1.70E-02	24.0
Manufacturing	8.32E-03	11.9	4.36E-03	0.792	6.46E-03	9.15
Use/application	4.60E-02	65.9	4.66E-02	8.45	4.66E-02	66.0
End-of-life	7.11E-04	1.02	6.22E-04	0.113	6.18E-04	0.876
Total	**6.98E-02**	**100**	**5.51E-01**	**100**	**7.06E-02**	**100**

*The impact scores are in units of kg ethene-equivalents/1,000 cubic centimeters of solder applied to a printed wiring board.

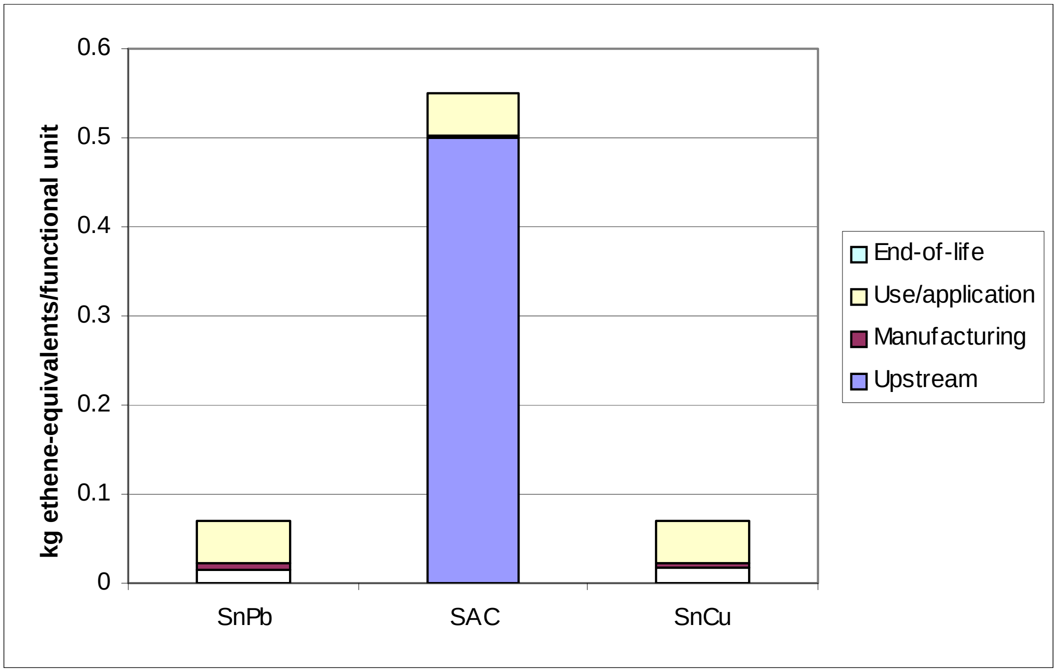


Figure 3-16. Bar Solder Total Life-Cycle Impacts: Photochemical Smog

As shown in the table and figure, SAC solder has the greatest impact category indicator at 0.551 kg of ethene-equivalents/functional unit for photochemical smog, followed by SnCu and SnPb, which are each about 7.8 times less than SAC and nearly equal to one another (0.0706 and 0.0698 kg ethene-equivalents, respectively). BSA and SnPb results are substantially lower with photochemical smog impact indicators of 0.361 and 0.313 kg ethene-equivalents, respectively. Nearly 91 percent of the SAC smog impacts are driven by the upstream stage, while SnPb and SnCu are driven first by the use/application stage (66 percent for both), followed by the upstream stage (21 and 24 percent, respectively). Bar solder manufacturing contributes a greater percent for SnPb and SnCu than for SAC; however, the magnitude of the manufacturing impacts for each alloy is on the same order of magnitude (0.0083, 0.0044, 0.0065 kg ethene-equivalents). EOL processes contribute very little to the overall smog impact scores for any of the alloys.

Photochemical Smog Impacts by Process Group (Bar Solder)

Table 3-46 lists the photochemical smog impact scores for each of the processes in the life-cycle of a bar solder. For SAC, smog impacts from upstream processes are due primarily to the silver production process, even though silver is only a small proportion of the alloy composition. For example, silver production contributes 87 percent of the total smog impacts for SAC, while the percent composition of silver is only 3.9 percent. For SnPb, which is composed of 63 percent tin, only 14 percent of smog impacts are due to tin production. For SnPb and SnCu, there is a greater percentage of impacts from tin, which is greater by mass than either lead or Copper.

Table 3-46. Photochemical smog impacts by life-cycle stage and process group (bar solder)

Life-cycle stage	**SnPb**		**SAC**		**SnCu**	
Process group	Score*	%	Score*	%	Score*	%
UPSTREAM						
Sn production	9.95E-03	14.2	2.11E-02	3.82	1.63E-02	23.0
Pb production	4.79E-03	6.86	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	4.77E-01	86.7	N/A	N/A
Cu production	N/A	N/A	7.13E-04	0.130	7.00E-04	0.991
Total	**1.47E-02**	**21.1**	**4.99E-01**	**90.6**	**1.70E-02**	**24.0**
MANUFACTURING						
Solder manufacturing	1.02E-03	1.46	1.41E-03	0.255	1.40E-03	1.98
Post-industrial recycling	7.31E-03	10.5	2.95E-03	0.536	5.06E-03	7.17
Total	**8.32E-03**	**11.9**	**4.36E-03**	**0.792**	**6.46E-03**	**9.15**
USE/APPLICATION						
Solder application	4.60E-02	65.9	4.66E-02	8.45	4.66E-02	66.0
Total	**4.60E-02**	**65.9**	**4.66E-02**	**8.45**	**4.66E-02**	**66.0**
END-OF-LIFE						
Landfill	1.20E-04	0.173	1.05E-04	0.0191	1.05E-04	0.148
Incineration	-1.16E-04	-0.166	-1.02E-04	-0.0184	-1.01E-04	-0.143
Demanufacturing	3.18E-05	0.0455	2.78E-05	0.0050	2.76E-05	0.0391
Cu smelting	6.75E-04	0.968	5.91E-04	0.107	5.87E-04	0.831
Unregulated	0.00E+00	0.0000	0.00E+00	0.0000	0.00E+00	0.0000
Total	**7.11E-04**	**1.02**	**6.22E-04**	**0.113**	**6.18E-04**	**0.876**
GRAND TOTAL	**6.98E-02**	**100**	**5.51E-01**	**100**	**7.06E-02**	**100**

*The impact scores are in units of ethene-equivalents/1,000 cubic centimeter of solder applied to a printed wiring board.
N/A=not applicable

As with other impact categories, impacts from the use/application life-cycle stage are entirely from the solder reflow process group. Within the manufacturing life-cycle stage, the post-industrial recycling process is a greater contributor than solder manufacturing for all bar solder alloys, and varies among solder alloys depending on the percent of metals recycled.

EOL processes contribute 1 percent or less of the total photochemical smog impacts for any of the solders, with the majority coming from smelting processes used to recover copper and other valuable metals from waste electronics. The landfilling process group, which includes diesel fuel production, is the second greatest contributor to EOL impacts. Demanufacturing contributes less than 0.05 percent for each alloy, and incineration results in a credit based on the surplus energy generated during the incineration of electronics at EOL.

Top Contributors to Photochemical Smog Impacts (Bar Solder)

Table 3-47 presents the specific materials or flows contributing at least 1 percent of photochemical smog impacts by solder. The results show that most of the top contributors are from either the use/application stage or the upstream life-cycle stage. Sulphur dioxide is the largest contributing individual flow, and is emitted in largely contributing quantities during electricity production and metals production.

Table 3-47. Top contributors to photochemical smog impacts (bar solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	Use/application	Electricity generation	Sulphur dioxide	46.3
	Upstream	Tin production	Sulphur dioxide	13.4
	Use/application	Electricity generation	NMVOC (unspecified)	10.9
	Upstream	Lead production	Sulphur dioxide	5.07
	Manufacturing	Heavy fuel oil (#6) for post-industrial recycling	NMVOC (unspecified)	4.70
	Manufacturing	Electricity generation for post-industrial recycling	Sulphur dioxide	3.50
	Use/application	Electricity generation	Carbon monoxide	3.11
	Use/application	Electricity generation	Xylene (dimethyl benzene)	1.75
	Use/application	Electricity generation	Methane	1.37
SAC	Upstream	Silver production	Sulphur dioxide	79.9
	Use/application	Electricity generation	Sulphur dioxide	5.93
	Upstream	Silver production	NMVOC (unspecified)	5.60
	Upstream	Tin production	Sulphur dioxide	3.61
	Use/application	Electricity generation	NMVOC (unspecified)	1.39
SnCu	Use/application	Electricity generation	Sulphur dioxide	46.3
	Upstream	Tin production	Sulphur dioxide	21.7
	Use/application	Electricity generation	NMVOC (unspecified)	10.9
	Use/application	Electricity generation	Carbon monoxide	3.11
	Use/application	Electricity generation	Xylene (dimethyl benzene)	1.75
	Manufacturing	Electricity generation for post-industrial recycling	Sulphur dioxide	1.64
	Use/application	Electricity generation	Methane	1.37
	Upstream	Tin production	Carbon monoxide	1.13

For SnPb, sulphur dioxide from the generation of electricity used in wave soldering contributes about 46 percent to the total smog impact score. Other flows from the use/application stage for electricity generation, such as unspecified NMVOCs, carbon monoxide, xylene, and methane, all contribute at least 1 percent each to the total smog impact score for SnPb. Other flows for SnPb that are from metals production include sulphur dioxide from tin production (13 percent) and sulphur dioxide from lead production (5 percent). The manufacturing stage also contributes 4.7 percent from unspecified NMVOCs and 3.5 percent from sulphur dioxide, both emitted during post-industrial recycling. The top contributors to the SnCu alloy are similar to those from SnPb, except that there are no contributions from the lead production process.

Sulphur dioxide resulting from the electricity used in both solder application and silver production also is the greatest contributor for the SAC alloy. The percent contribution from sulphur dioxide from both electricity generation for the use/application stage and silver production combined is approximately 86 percent. Unspecified NMVOCs also contribute at least 1 percent from both silver production and electricity generation during application. For the extraction and processing inventories (e.g., silver production), the secondary data sources do not distinguish whether the smog-inducing substances are emitted from electric power used or directly released during extraction and processing.

3.2.6.4 Limitations and uncertainties

For the paste solder results, the two processes that have the top contribution to photochemical smog impacts are electricity generation for solder reflow application (for all alloys) and silver production (for the lead-free alloys). As presented earlier, the same sources of uncertainty from the use/application stage inventory apply: (1) energy consumed during application/use of the solder paste is based on a limited number of data points that cover a wide range, and (2) electricity production data were from a secondary source. Energy consumption during reflow is the subject of a sensitivity analysis in Section 3.3.

For the bar solder results, the wave application data are expected to be representative of general wave operations and are of good quality. The remaining uncertainty, again not expected to be too large, is that the electricity production data that are linked to the wave operations are from secondary data.

Uncertainties related to the silver inventory are described earlier in Section 3.2.1.4, which concludes that although the GaBi inventory used in this analysis is considered “good” by GaBi, there remains enough uncertainty that it is the subject of a sensitivity analysis presented in Section 3.3.

Uncertainty in the smog results also is derived from the impact assessment methodology, which uses the mass of a chemical released to air per functional unit and the chemical-specific partial equivalency factor. The equivalency factor is a measure of a chemical’s POCP compared to the reference chemical ethene. As noted in Section 3.1.2, photochemical smog impacts are based on partial equivalency because some chemicals cannot be converted into POCP equivalency factors (e.g., nitrogen oxide). The inability to develop equivalency factors for some chemicals is a limitation of the photochemical smog impact assessment methodology.

3.2.7 Acidification Impacts

3.2.7.1 Characterization

Acidification impacts refer to the release of chemicals that may contribute to the formation of acid precipitation. Impact characterization is based on the amount of a chemical released to air that would cause acidification and the acidification potentials (AP) equivalency factor for that chemical. The AP equivalency factor is the number of hydrogen ions that can theoretically be formed per mass unit of the pollutant being released compared to sulfur dioxide (SO_2) (Heijungs *et al.*, 1992; Hauschild and Wenzel, 1997). Appendix D lists the AP values that were used as the basis of calculating acidification impacts. The impact score is calculated by:

$$(IS_{AP})_i = (EF_{AP} \times Amt_{AC})_i$$

where:

IS_{AP}	equals the impact score for acidification for chemical *i* (kg SO_2 equivalents) per functional unit;
EF_{AP}	equals the AP equivalency factor for chemical *i* (SO_2 equivalents) (Appendix D); and
Amt_{AC}	equals the amount of acidification chemical *i* released to the air (kg) per functional unit.

3.2.7.2 Paste solder results

Total Acidification Impacts by Life-Cycle Stage (Paste Solder)

Table 3-48 presents the solder paste results for acidification impacts by life-cycle stage, based on the impact assessment methodology presented above. The table lists the acidification impact scores per functional unit for the life-cycle stages of each solder paste alloy, as well as the percent contribution of each life-cycle stage to the total impacts. Figure 3-17 presents the results in a stacked bar chart.

Table 3-48. Acidification impacts by life-cycle stage (paste solder)

Life-cycle stage	SnPb		SAC		BSA		SABC	
	Score*	%	Score*	%	Score*	%	Score*	%
Upstream	3.94E-01	6.06	6.74E+00	54.0	2.85E+00	38.9	4.51E+00	43.9
Manufacturing	7.13E-02	1.10	7.59E-02	0.608	4.35E-02	0.594	7.59E-02	0.739
Use/application	6.03E+00	92.8	5.66E+00	45.4	4.43E+00	60.5	5.68E+00	55.3
End-of-life	4.33E-03	0.0666	3.75E-03	0.0300	-1.40E-04	-0.0019	3.76E-03	0.0366
Total	**6.50E+00**	**100**	**1.25E+01**	**100**	**7.32E+00**	**100**	**1.03E+01**	**100**

*The impact scores are in units of kilograms SO_2-equivalents/1,000 cubic centimeters of solder applied to a printed wiring board.

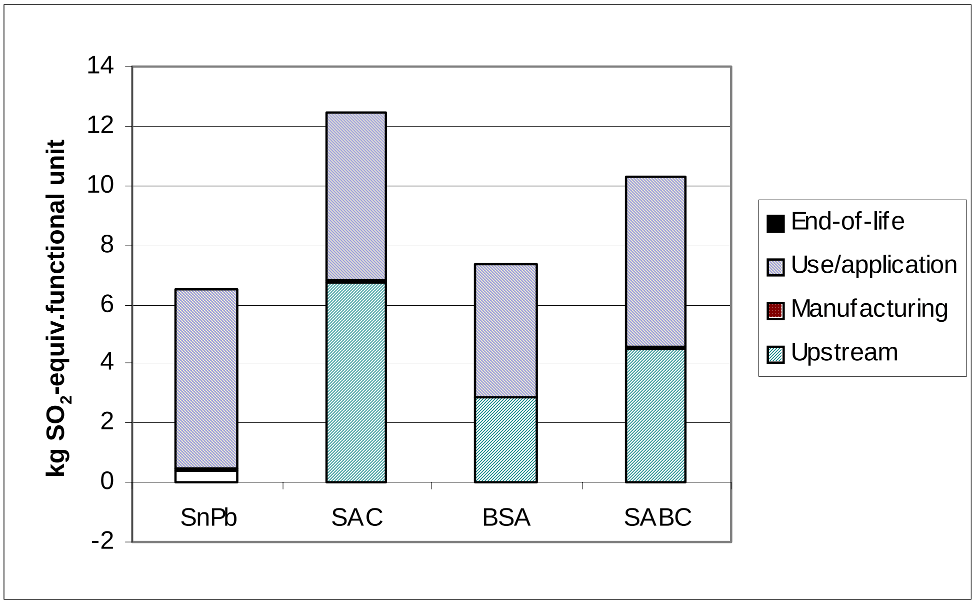


Figure 3-17. Solder Paste Total Life-Cycle Impacts: Acidification

As shown in the table and figure, SAC solder has the greatest impact category indicator for acidification with 12.5 kg of SO_2-equivalents/functional unit, followed by SABC at 10.3 kg SO_2-equivalents, BSA at 7.32 kg SO_2-equivalents/functional unit, and SnPb with the lowest indicator at 6.50 kg SO_2-equivalents/functional unit. Approximately 93 percent of the SnPb life-cycle acidification impacts are driven by the use/application stage, while the lead-free impacts are driven by both the upstream and use/application stages. Contributions from solder manufacturing (less than 1.5 percent of the total life cycle impacts) and EOL processes (less than 0.07 percent) were minimal for all alloys.

Acidification Impacts by Process Group (Paste Solder)

Table 3-49 lists the acidification impacts of each of the processes in the life-cycle of the solder pastes. The production of energy consumed during the reflow of each of the alloys is the single greatest contributor for all of the alloys. For the lead-free alloys, upstream processes are also large contributors, mainly from the silver production process, even though silver comprises only a small proportion of their compositions. For example, silver production contributes 26 to 50 percent of the total acidification impact scores for the lead-free solder alternatives, while the percent composition of silver ranges from only 1 to 3.9 percent. For BSA, which is composed of 57 percent bismuth, about 10 percent of acidification impacts are due to bismuth production.

Table 3-49. Acidification impacts by life-cycle stage and process group (paste solder)

Life-cycle stage	**SnPb**		**SAC**		**BSA**		**SABC**	
Process group	Score*	%	Score*	%	Score*	%	Score*	%
UPSTREAM								
Sn production	3.06E-01	4.71	4.48E-01	3.59	2.30E-01	3.14	4.52E-01	4.40
Pb production	8.77E-02	1.35	N/A	N/A	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	6.28E+00	50.3	1.88E+00	25.6	4.04E+00	39.3
Cu production	N/A	N/A	8.07E-03	0.0647	N/A	N/A	6.75E-03	0.0657
Bi production	N/A	N/A	N/A	N/A	7.45E-01	10.17	1.13E-02	0.110
Total	**3.94E-01**	**6.06**	**6.74E+00**	**54.0**	**2.85E+00**	**38.9**	**4.51E+00**	**43.9**
MANUFACTURING								
Solder manufacturing	2.56E-02	0.394	3.96E-02	0.317	2.48E-02	0.339	3.97E-02	0.387
Post-industrial recycling	4.57E-02	0.704	3.63E-02	0.291	1.87E-02	0.255	3.62E-02	0.352
Total	**7.13E-02**	**1.10**	**7.59E-02**	**0.608**	**4.35E-02**	**0.594**	**7.59E-02**	**0.739**
USE/APPLICATION								
Reflow application	6.03E+00	92.8	5.66E+00	45.4	4.43E+00	60.5	5.68E+00	55.3
Total	**6.03E+00**	**92.8**	**5.66E+00**	**45.4**	**4.43E+00**	**60.5**	**5.68E+00**	**55.3**
END-OF-LIFE								
Landfill	7.51E-05	0.0012	6.50E-05	0.0005	8.03E-05	0.0011	6.52E-05	0.0006
Incineration	-7.70E-04	-0.0119	-6.67E-04	-0.0053	-8.24E-04	-0.0113	-6.69E-04	-0.0065
Demanufacturing	5.93E-04	0.0091	5.13E-04	0.0041	6.04E-04	0.0082	5.15E-04	0.0050
Cu smelting	4.43E-03	0.0682	3.84E-03	0.0307	N/A	N/A	3.85E-03	0.0375
Unregulated	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00
Total	**4.33E-03**	**0.0666**	**3.75E-03**	**0.0300**	**-1.40E-04**	**-0.0019**	**3.76E-03**	**0.0366**
GRAND TOTAL	**6.50E+00**	**100**	**1.25E+01**	**100**	**7.32E+00**	**100**	**1.03E+01**	**100**

*The impact scores are in units of kilograms SO^2-equivalents/1,000 cubic centimeters of solder applied to a printed wiring board.
N/A=not applicable

Within the manufacturing life-cycle stage, the post-industrial recycling process is a greater contributor than solder manufacturing for all solder paste alloys except BSA. The distribution of the manufacturing impacts between these two processes is similar to that found for energy, and is discussed in Section 3.2.2. The manufacturing stage is a small contributor overall. Likewise, EOL processes do not add significantly to acidification, contributing no more than 0.07 percent of the total acidification impact score for any solder alloy. The majority of EOL acidification impacts come from smelting processes used to recover copper and other valuable metals from waste electronics (contributions range from 0.031 to 0.037 percent of overall impacts for solders containing copper).

Top Contributors to Acidification Impacts (Paste Solder)

Table 3-50 presents the specific materials or flows contributing a minimum of 1 percent of acidification impacts by solder. As expected from the results above, all the top contributors are from either the use/application stage or the upstream life-cycle stage. Only three materials contribute greater than 1 percent: sulphur dioxide, nitrogen oxides, and hydrogen chloride (hydrochloric acid). Sulphur dioxide is the largest contributor for all of the alloys, mostly from electricity generation in the use/application stage and silver production (for alloys containing silver). Nitrogen oxides are the second greatest contributor, mostly from electricity in the use/application stage.

Table 3-50. Top contributors to acidification impacts (paste solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	Use/application	Electricity generation	Sulphur dioxide	65.4
	Use/application	Electricity generation	Nitrogen oxides	24.4
	Upstream	Tin production	Sulphur dioxide	3.10
	Use/application	Electricity generation	Hydrogen chloride	1.64
	Upstream	Tin production	Nitrogen oxides	1.62
	Upstream	Lead production	Sulphur dioxide	1.27
SAC	Upstream	Silver production	Sulphur dioxide	49.5
	Use/application	Electricity generation	Sulphur dioxide	32.0
	Use/application	Electricity generation	Nitrogen oxides	11.9
	Upstream	Tin production	Sulphur dioxide	2.36
	Upstream	Tin production	Nitrogen oxides	1.23
BSA	Use/application	Electricity generation	Sulphur dioxide	42.7
	Upstream	Silver production	Sulphur dioxide	25.2
	Use/application	Electricity generation	Nitrogen oxides	15.9
	Upstream	Bismuth production	Sulphur dioxide	9.91
	Upstream	Tin production	Sulphur dioxide	2.06
	Upstream	Tin production	Nitrogen oxides	1.08
	Use/application	Electricity generation	Hydrogen chloride	1.07
SABC	Use/application	Electricity generation	Sulphur dioxide	39.0
	Upstream	Silver production	Sulphur dioxide	38.7
	Use/application	Electricity generation	Nitrogen oxides	14.5
	Upstream	Tin production	Sulphur dioxide	2.89
	Upstream	Tin production	Nitrogen oxides	1.51

For SnPb solder, sulphur dioxide and nitrogen oxides from electricity produced for the use/application stage contribute approximately 66 and 25 percent to the total SnPb acidification impacts, respectively. Other individual flows from the upstream processes for SnPb contribute less than 3 percent each.

For the lead-free solders, the percent contribution of sulphur dioxide from both electricity generation (for the use/application stage) and silver production combined ranges from 68 to 82 percent. Nitrogen oxides from electricity generation in the use/application stage are the second greatest contributors for the lead-free alloys, accounting for about 12 to 16 percent of total impacts. Flows of sulfur dioxide and nitrogen oxides from tin production contribute about 3 percent or less to acidification impacts for the different alloys, while flows from bismuth production contribute about 10 percent of BSA's acidification impacts. BSA has the highest bismuth content of all the alloys at 57 percent. The extraction and processing inventories are from secondary data sources that do not distinguish whether the acidification-inducing substances are emitted during electricity generation or emitted directly during extraction and processing itself.

3.2.7.3 Bar solder results

Total Acidification Impacts by Life-Cycle Stage (Bar Solder)

Table 3-51 presents the solder paste results for acidification impacts by life-cycle stage, based on the impact assessment methodology presented in Sect 3.2.7.1. The table lists the acidification impact scores per functional unit for the life-cycle stages of each solder paste alloy, as well as the percent contribution of each life-cycle stage to the total impacts. Figure 3-18 presents the results in a stacked bar chart.

Table 3-51. Acidification impacts by life-cycle stage (bar solder)

Life-cycle stage	**SnPb**		**SAC**		**SnCu**	
	Score*	%	Score*	%	Score*	%
Upstream	3.76E-01	26.3	9.97E+00	90.8	5.00E-01	32.7
Manufacturing	9.22E-02	6.46	4.39E-02	0.400	5.95E-02	3.89
Use/application	9.54E-01	66.9	9.65E-01	8.79	9.65E-01	63.2
End-of-life	4.86E-03	0.340	4.25E-03	0.0387	4.22E-03	0.276
Total	**1.43E+00**	**100**	**1.10E+01**	**100**	**1.53E+00**	**100**

*The impact scores are in units of kg SO_2-equivalents/1,000 cc of solder applied to a printed wiring board.

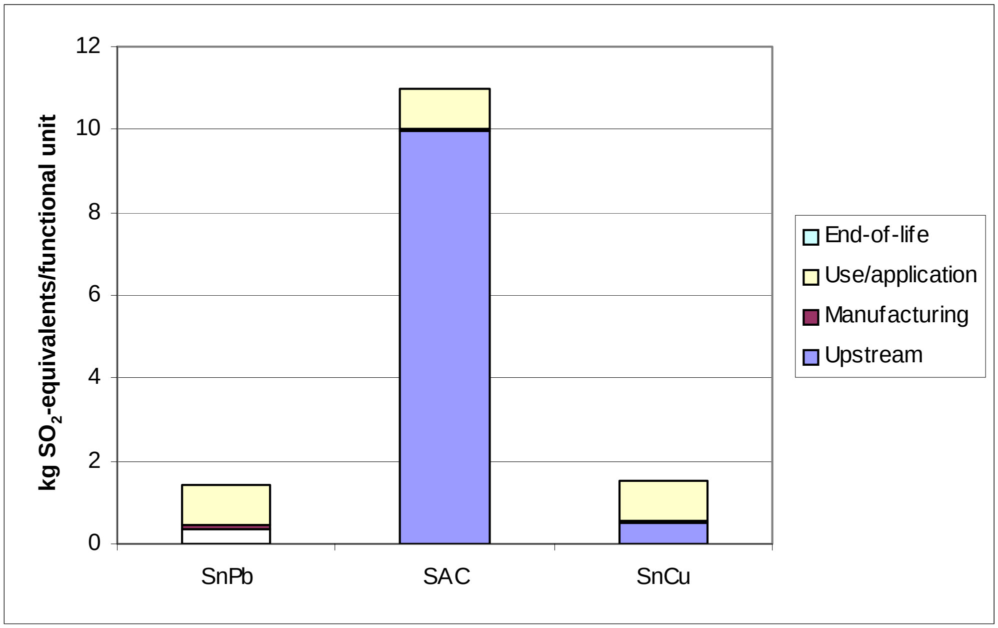


Figure 3-18. Bar Solder Total Life-Cycle Impacts: Acidification

As shown in the table and figure, SAC solder has the greatest impact category indicator for acidification with 11 kg of SO_2-equivalents/functional unit, followed by SnCu at 1.5 kg SO_2-equivalents and SnPb at 1.4 kg SO_2-equivalents/functional unit. Nearly 91 percent of the SAC life-cycle acidification impacts are driven by the upstream stage. The SnCu impacts are only slightly higher (approximately 7 percent higher) than SnPb. The use/application stage scores are approximately equal for each alloy; however, this stage contributes a greater percent to the total SnPb and SnCu impacts due to the much lower impacts from the upstream stage. Contributions from solder manufacturing (less than 7 percent of the total life cycle impacts) and EOL processes (less than 0.4 percent) were small to minimal for all alloys.

Acidification Impacts by Process Group (Bar Solder)

Table 3-52 lists the acidification impacts of each of the processes in the life-cycle of the bar solders. The production of energy consumed during wave solder application is the single greatest contributor for the SnPb and SnCu alloys (67 and 63 percent, respectively). For SAC, silver production in the upstream life-cycle stage is the largest contributor (85 percent) to all SAC impacts, even though silver comprises only a small proportion of its composition. For SnPb and SnCu, tin production is the second greatest contributor to total impacts (21 and 32 percent, respectively).

Within the manufacturing life-cycle stage, the post-industrial recycling process is a greater contributor than solder manufacturing for SnPb and SnCu, while it is equal for SAC. The distribution of the manufacturing impacts between these two processes depends mostly on the different melting points of the alloys and varying secondary alloy content among the alloys, which are discussed in Chapter 2. The manufacturing stage is a small contributor overall.

Likewise, EOL processes do not add significantly to acidification, contributing no more than 0.34 percent of the total acidification impact score for any solder alloy. The majority of EOL acidification impacts come from smelting processes used to recover copper and other valuable metals from waste electronics.

Table 3-52. Acidification impacts by life-cycle stage and process group (bar solder)

Life-cycle stage	**SnPb**		**SAC**		**SnCu**	
Process group	Score*	%	Score*	%	Score*	%
UPSTREAM						
Sn production	2.98E-01	20.9	6.30E-01	5.74	4.86E-01	31.8
Pb production	7.83E-02	5.49	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	9.32E+00	84.9	N/A	N/A
Cu production	N/A	N/A	1.35E-02	0.123	1.32E-02	0.865
Total	**3.76E-01**	**26.3**	**9.97E+00**	**90.8**	**5.00E-01**	**32.7**
MANUFACTURING						
Solder manufacturing	1.52E-02	1.07	2.20E-02	0.200	2.18E-02	1.43
Post-industrial recycling	7.70E-02	5.40	2.20E-02	0.200	3.76E-02	2.46
Total	**9.22E-02**	**6.46**	**4.39E-02**	**0.400**	**5.95E-02**	**3.89**
USE/APPLICATION						
Solder application	9.54E-01	66.9	9.65E-01	8.79	9.65E-01	63.2
Total	**9.54E-01**	**66.9**	**9.65E-01**	**8.79**	**9.65E-01**	**63.2**
END-OF-LIFE						
Landfill	8.34E-05	0.0058	7.30E-05	0.0007	7.25E-05	0.0047
Incineration	-8.11E-04	-0.0568	-7.10E-04	-0.0065	-7.05E-04	-0.0461
Demanufacturing	6.58E-04	0.0461	5.76E-04	0.0052	5.72E-04	0.0374
Cu smelting	4.93E-03	0.345	4.31E-03	0.0393	4.28E-03	0.280
Unregulated	0.00E+00	0.0000	0.00E+00	0.0000	0.00E+00	0.0000
Total	**4.86E-03**	**0.340**	**4.25E-03**	**0.0387**	**4.22E-03**	**0.276**
GRAND TOTAL	**1.43E+00**	**100**	**1.10E+01**	**100**	**1.53E+00**	**100**

*The impact scores are in units of kg SO_2-equivalents/1,000 cc of solder applied to a printed wiring board.
N/A=not applicable

Top Contributors to Acidification Impacts (Bar Solder)

Table 3-53 presents the specific materials or flows contributing a minimum of 1 percent of acidification impacts by solder. As expected from the results above, nearly all the top contributors are from either the use/application stage or the upstream life-cycle stage. Outputs from post-industrial recycling from the manufacturing stage also contribute greater than 1 percent to total impacts. Only these materials contribute greater than 1 percent: sulphur dioxide, nitrogen oxides, and hydrogen chloride (hydrochloric acid). Sulphur dioxide is the largest contributor for all of the alloys, mostly from electricity generation in the use/application stage or silver production (for SAC). Nitrogen oxides are the second greatest contributor, mostly from electricity in the use/application stage.

Table 3-53. Top contributors to acidification impacts (bar solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	Use/application	Electricity generation	Sulphur dioxide	47.2
	Use/application	Electricity generation	Nitrogen oxides	17.6
	Upstream	Tin production	Sulphur dioxide	13.7
	Upstream	Tin production	Nitrogen oxides	7.16
	Manufacturing	Electricity generation for post-industrial recycling	Sulphur dioxide	3.57
	Manufacturing	Electricity generation for post-industrial recycling	Nitrogen oxides	1.33
	Use/application	Electricity generation	Hydrogen chloride	1.18
SAC	Upstream	Silver production	Sulphur dioxide	83.5
	Use/application	Electricity generation	Sulphur dioxide	6.20
	Upstream	Tin production	Sulphur dioxide	3.77
	Use/application	Electricity generation	Nitrogen oxides	2.31
	Upstream	Tin production	Nitrogen oxides	1.97
	Upstream	Silver production	Nitrogen oxides	1.34
SnCu	Use/application	Electricity generation	Sulphur dioxide	44.5
	Upstream	Tin production	Sulphur dioxide	20.9
	Use/application	Electricity generation	Nitrogen oxides	16.6
	Upstream	Tin production	Nitrogen oxides	10.9
	Manufacturing	Electricity generation for post-industrial recycling	Sulphur dioxide	1.57
	Use/application	Electricity generation	Hydrogen chloride	1.12

For SnPb solder, sulphur dioxide and nitrogen oxides from electricity produced for the use/application stage contribute approximately 47 and 18 percent to the total SnPb acidification impacts, respectively. Other individual flows from the upstream and manufacturing processes for SnPb contribute 7 percent or lower. The top contributors to SnCu are similar to SnPb.

For SAC, on the other hand, the percent contribution of sulphur dioxide from silver production is the top contributor at approximately 84 percent. Sulphur dioxide and nitrogen oxides from electricity generation (for the use/application stage) and from tin and silver production also are in the top contributors list (6 percent and less). The ME&P inventories are from secondary data sources that do not distinguish whether the acidification-inducing substances are emitted during electricity generation or emitted directly during extraction and processing itself.

3.2.7.4 Limitations and uncertainties

For the paste solder results, the two processes with the greatest contribution to acidification impacts are electricity generation for the reflow application of solder (for all alloys) and silver production (for the lead-free alloys). Similarly, for the wave solder results, wave application (for SnPb and SnCu) and silver production (for SAC) are the top contributors to acidification impacts. Acidification LCIA results are subject to the same sources of uncertainty in the use/application stage inventory and silver production inventory as discussed previously. For reflow solders, the greatest uncertainties are related to (1) reflow energy during application/use is based on a limited number of data points that cover a wide range, (2) electricity production data employed in the use/application stage are from a secondary source, and (3) the magnitude of many of the flows in the GaBi silver inventory used in this analysis varies considerably from those in an alternate inventory available from DEAM. Energy consumed during the reflow process is the subject of a sensitivity analysis in Section 3.3. Section 3.3 also presents an alternate analysis using the DEAM silver inventory. The same uncertainties associated with electricity production as a secondary source and the silver inventory apply to the wave solder results. As discussed in previous sections, there is less uncertainty associated with the wave application data than with the reflow application data.

Uncertainty in the acidification results also is derived from the impact assessment methodology. Acidification impact characterization is a function of the mass of an acid-forming chemical emitted to air and the AP equivalency factor for that chemical. The AP equivalency factor is the number of hydrogen ions that can theoretically be formed per unit mass of the pollutant being released compared to SO_2. This is a full equivalency approach to impact characterization where all substances are addressed in a unified, technical model that lends more certainty to the characterization results than partial equivalency factors discussed with regard to photochemical smog (Section 3.2.6).

3.2.8 Air Particulate Impacts

3.2.8.1 Characterization

Air particulate impacts refers to the release and build up of particulate matter primarily from combustion processes. Impact scores are based on the amount released to the air of particulate matter with average aerodynamic diameter less than 10 micrometers (PM_{10}), the size of particulate matter that is most damaging to the respiratory system. Impact characterization is simply based on the inventory amount of particulates released to air. This loading impact score is calculated by:

$$IS_{PM} = Amt_{PM}$$

where:

IS_{PM}	equals the impact score for particulate (kg PM_{10}) per functional unit, and
Amt_{PM}	equals the inventory amount of particulate release (PM_{10}) to the air (kg) per functional unit.

In this equation, PM_{10} is used to estimate impacts; however, if only TSP data are available, these data are used. Using TSP data is an overestimation of $PM_{10,}$ which only refers to the fraction of particulates in the size range below 10 micrometers. A common conversion factor (TSP to PM_{10}) is not available because the fraction of PM_{10} varies depending on the type of particulates. The particulate matter impact category not only serves to represent potential health effects associated with particulates (e.g., respiratory impacts), but also winter smog which consists partially of suspended particulate matter or fine dust and soot particles. Winter smog is distinguished from summer smog (e.g., photochemical smog, which is the build up of tropospheric ozone concentrations due to VOCs and nitrogen oxides in the presence of sunlight). Winter smog is a problem that occurs mainly in Eastern Europe and has been the cause of health-related deaths in the past (Goedkoop, 1995).

3.2.8.2 Paste solder results

Total Air Particulate Impacts by Life-Cycle Stage (Paste Solder)

Table 3-54 presents the solder paste results for air particulate impacts by life-cycle stage, based on the impact assessment methodology presented in above. The table lists the air particulate impact scores per functional unit for the life-cycle stages of each solder paste alloy, as well as the percent contribution of each life-cycle stage to the total impacts. Figure 3-19 presents the results in a stacked bar chart.

Table 3-54. Air particulate impacts by life-cycle stage (paste solder)

Life-cycle stage	SnPb		SAC		BSA		SABC	
	Score*	%	Score*	%	Score*	%	Score*	%
Upstream	8.78E-02	19.4	9.57E-01	73.7	3.18E-01	54.3	6.62E-01	65.8
Manufacturing	6.28E-03	1.39	6.23E-03	0.480	4.15E-03	0.710	6.24E-03	0.620
Use/application	3.58E-01	79.1	3.36E-01	25.8	2.63E-01	45.0	3.37E-01	33.5
End-of-life	3.08E-04	0.0682	2.67E-04	0.0205	3.76E-05	0.0064	2.68E-04	0.027
Total	**4.52E-01**	**100**	**1.30E+00**	**100**	**5.85E-01**	**100**	**1.01E+00**	**100**

*The impact scores are in units of kilograms of particulate matter/1,000 cubic centimeters of solder applied to a printed wiring board.

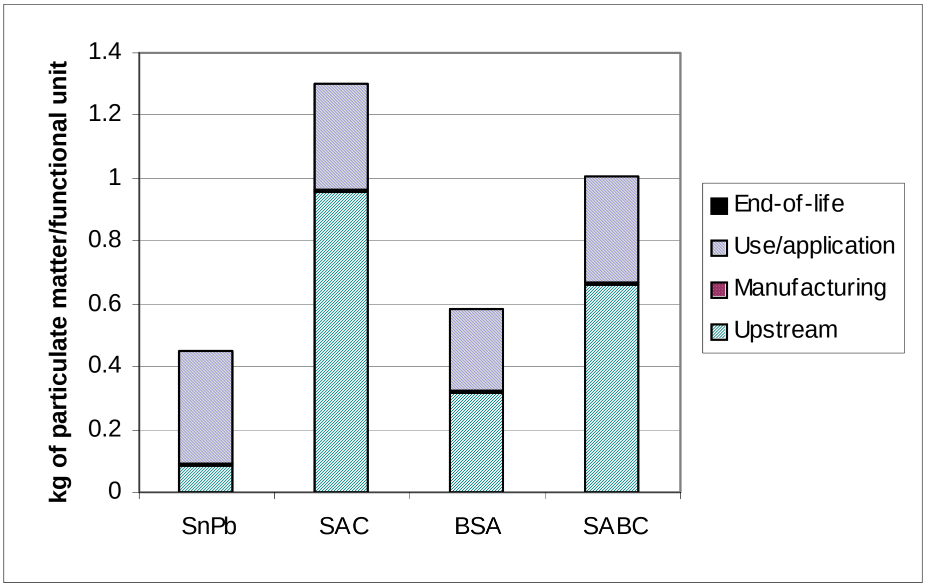


Figure 3-19. Solder Paste Total Life-Cycle Impacts: Air Particulates

As shown in the table and figure, SAC solder has the greatest impact category indicator for air particulates (1.30 kg particulate matter/functional unit), followed by SABC at 1.01 kg particulate matter/functional unit. BSA and SnPb results are much lower with impact category indicators of about 0.58 and 0.45 kg particulate matter/functional unit, respectively. For the SnPb alloy, approximately 79 percent of the life-cycle air particulate impact score is driven by the use/application stage, while 19 percent results from upstream processes. Unlike SnPb, the lead-free alternatives receive greater contributions from the upstream stage than from the use/application stage. Of the lead-free alternatives, SAC receives the greatest contribution from upstream impacts at 74 percent, while BSA receives the lowest at 54 percent. The use/application stage constitutes nearly all the remaining impacts for each lead-free alloy. Solder manufacturing contributes less than 1.4 percent of the total air particulate impacts, while EOL processes contribute 0.07 percent or less for any of the individual solder paste alloys.

Air Particulate Impacts by Process Group (Paste Solder)

Table 3-55 lists the air particulate impact scores for each of the processes in the life-cycle of the solder pastes. For SAC and SABC, silver production is the greatest contributor to total air particulate impacts, while electricity generation in the use stage is the greatest contributor for the SnPb and BSA alloys. As expected, given their greater silver content, impacts from silver production are greater for SAC and SABC than for BSA. As with other impact categories, however, the limited silver content of all the silver-bearing alloys results in disproportionately high impacts from silver production compared to the other metals. For example, silver production contributes 42 to 64 percent of the total air particulate impacts for the lead-free solder alternatives, while the percent composition of silver in those alloys never exceeds 3.9 percent.

Table 3-55. Air particulate impacts by life-cycle stage and process group (paste solder)

Life-cycle stage	**SnPb**		**SAC**		**BSA**		**SABC**	
Process group	Score*	%	Score*	%	Score*	%	Score*	%
UPSTREAM								
Sn production	8.63E-02	19.1	1.26E-01	9.72	6.47E-02	11.1	1.27E-01	12.7
Pb production	1.49E-03	0.329	N/A	N/A	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	8.31E-01	63.9	2.48E-01	42.4	5.35E-01	53.2
Cu production	N/A	N/A	3.93E-05	0.0030	N/A	N/A	3.29E-05	0.0033
Bi production	N/A	N/A	N/A	N/A	4.85E-03	0.830	7.34E-05	0.0073
Total	**8.78E-02**	**19.4**	**9.57E-01**	**73.7**	**3.18E-01**	**54.3**	**6.62E-01**	**65.8**
MANUFACTURING								
Solder manufacturing	2.62E-03	0.580	3.32E-03	0.256	2.66E-03	0.454	3.34E-03	0.332
Post-industrial recycling	3.66E-03	0.809	2.91E-03	0.224	1.50E-03	0.256	2.90E-03	0.288
Total	**6.28E-03**	**1.39**	**6.23E-03**	**0.480**	**4.15E-03**	**0.710**	**6.24E-03**	**0.620**
USE/APPLICATION								
Reflow application	3.58E-01	79.1	3.36E-01	25.8	2.63E-01	45.0	3.37E-01	33.5
Total	**3.58E-01**	**79.1**	**3.36E-01**	**25.8**	**2.63E-01**	**45.0**	**3.37E-01**	**33.5**
END-OF-LIFE								
Landfill	6.52E-06	0.0014	5.64E-06	0.0004	6.97E-06	0.0012	5.67E-06	0.0006
Incineration	-4.91E-06	-0.0011	-4.25E-06	-0.0003	-5.25E-06	-0.0009	-4.26E-06	-0.0004
Demanufacturing	3.52E-05	0.0078	3.04E-05	0.0023	3.58E-05	0.0061	3.06E-05	0.0030
Cu smelting	2.72E-04	0.0601	2.35E-04	0.0181	N/A	N/A	2.36E-04	0.0235
Unregulated	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00
Total	**3.08E-04**	**0.0682**	**2.67E-04**	**0.0205**	**3.76E-05**	**0.0064**	**2.68E-04**	**0.0266**
GRAND TOTAL	**4.52E-01**	**100**	**1.30E+00**	**100**	**5.85E-01**	**100**	**1.01E+00**	**100**

*The impact scores are in units of kilograms of particulate matter/1,000 cubic centimeters of solder applied to a printed wiring board.
N/A = not applicable

Tin, which has the greatest percent of the total composition in all the alloys except BSA, contributes between 10 and 19 percent to impacts for all alloys. Although BSA has a higher bismuth content (57 percent) than tin (42 percent), and the tin amount in BSA is less than the tin in the other alloys (ranging from 63 to 95.5 percent), tin still contributes approximately 11 percent to the total impacts, while bismuth contributes less than 1 percent. This indicates that tin has greater air particulate emissions than bismuth per unit of metal produced.

Emissions from the production of energy consumed during the reflow of each of the alloys contribute about 26 to 80 percent of the total air particulates score, depending on the alloy. The percent contribution of the use stage to SnPb impacts is up to 54 percent higher than its percent contribution to other alloys, even though the actual scores only differ by up to 26 percent. This is because SnPb upstream processes emit considerably less air particulates than those of the silver-containing alloys.

The manufacturing stage is a small contributor overall. SnPb, SAC, and SABC have nearly the same total manufacturing impact scores (approximately 0.006 kg particulate matter/functional unit), all of which are greater than the impacts from BSA (0.004 kg particulate matter/functional unit). Despite the similar total manufacturing impacts for SnPb, SAC, and SABC, there are differing contributions from the solder manufacturing and the post-industrial recycling processes. SnPb has more impacts from post-industrial recycling (0.0037 kg particulate matter/functional unit) than SAC and SABC (both at approximately 0.0029 kg particulate matter/functional unit). This is due to the fact that more secondary SnPb is used and generated from the post-industrial recycling process. SAC and SABC have lower secondary alloy content in the solder manufacturing process and, therefore, have lower post-industrial recycling impacts. The higher impacts from post-industrial recycling for SnPb are counter-balanced by the greater upstream impacts for the lead-free alternatives, which have greater virgin content in the alloys.

EOL processes are even smaller contributors to air particulates, accounting for no more than 0.07 percent of the total air particulates impact indicator for any solder alloy. The largest contributions result from smelting processes that recover copper and other valuable metals from waste electronics (percent contributions range from about 0.020 to 0.061 percent, for solders containing copper). The demanufacturing process group that includes electricity generation is the second greatest contributor to EOL impacts with between 0.0025 and 0.0079 percent contribution to total air particulate impacts. Landfilling is a very small contributor to air particulate impacts, less than 0.0015 percent for all alloys, and incineration results in a credit based on the surplus energy generated during energy incineration.

Top Contributors to Air Particulate Impacts (Paste Solder)

Table 3-56 presents the specific materials or flows contributing greater than 1 percent to air particulate impacts by solder. The only materials in the inventory that contribute to this impact category are unspecified dust and PM_{10}, and only unspecified dust contributes greater than1 percent. As expected from the results above, all the top contributors are from either the use/application stage or the upstream life-cycle stage.

For SnPb, dust emitted from electricity produced for the use/application stage contributes about 81 percent of total particulate impacts, and dust from tin production in the upstream stage contributes about 18 percent. The two lead-free alternative solders with the higher silver content, SAC and SABC, have the greatest impacts from dust emitted from the silver production process, 62 and 51 percent, respectively. BSA has the lowest silver content of the lead-free alternative solders. The life-cycle impacts of BSA are greatest from electricity generation from solder reflow application (48 percent), followed by silver production (40 percent), and tin production (11 percent). Tin production for all the alloys contributes between 9 and 18 percent. The ME&P inventories are from secondary data sources that do not distinguish whether the particulate matter is emitted from electric power used or directly released during extraction and processing.

Table 3-56. Top contributors to air particulate impacts (paste solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	Use/application	Electricity production	Dust (unspecified)	79.1
	Upstream	Tin production	Dust (unspecified)	19.1
SAC	Upstream	Silver production	Dust (unspecified)	63.9
	Use/application	Electricity production	Dust (unspecified)	25.8
	Upstream	Tin production	Dust (unspecified)	9.72
BSA	Use/application	Electricity production	Dust (unspecified)	45.0
	Upstream	Silver production	Dust (unspecified)	42.4
	Upstream	Tin production	Dust (unspecified)	11.1
SABC	Upstream	Silver production	Dust (unspecified)	53.2
	Use/application	Electricity production	Dust (unspecified)	33.5
	Upstream	Tin production	Dust (unspecified)	12.7

3.2.8.3 Bar solder results

Total Air Particulate Impacts by Life-Cycle Stage (Bar Solder)

Table 3-57 presents the bar solder results for air particulate impacts by life-cycle stage, based on the impact assessment methodology presented above in Section 3.2.8.1. The table lists the air particulate impact scores per functional unit for the life-cycle stages of each solder paste alloy, as well as the percent contribution of each life-cycle stage to the total impacts. Figure 3-20 presents the results in a stacked bar chart.

Table 3-57. Air particulate impacts by life-cycle stage (bar solder)

Life-cycle stage	**SnPb**		**SAC**		**SnCu**	
	Score*	%	Score*	%	Score*	%
Upstream	8.52E-02	57.1	1.41E+00	95.9	1.37E-01	68.9
Manufacturing	6.94E-03	4.66	2.95E-03	0.201	4.20E-03	2.11
Use/application	5.66E-02	38.0	5.73E-02	3.89	5.73E-02	28.8
End-of-life	3.43E-04	0.230	3.00E-04	0.0204	2.98E-04	0.150
Total	**1.49E-01**	**100**	**1.47E+00**	**100**	**1.99E-01**	**100**

*The impact scores are in units of kilograms of particulate matter/1,000 cubic centimeters of solder applied to a printed wiring board.

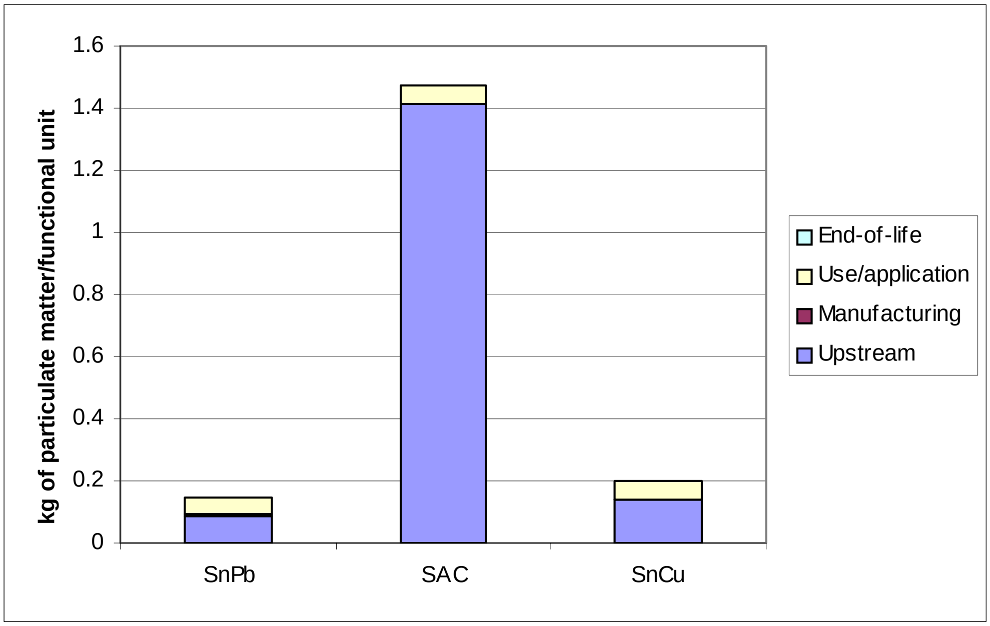


Figure 3-20. Bar Solder Total Life-Cycle Impacts: Air Particulates

As shown in the table and figure, SAC solder has the greatest impact category indicator for air particulates at 1.47 kg particulate matter/functional unit, followed by SnCu and SnPb at 0.199 and 0.149 kg particulate matter/functional unit, respectively. For the SnPb alloy, approximately 57 percent of the life-cycle air particulate impact score is driven by the upstream stage, while 38 percent results from the use/application stage. SnCu has greater impacts than SnPb from the upstream processes, which contribute approximately 69 percent to total SnCu impacts. The use/application stage for SnCu contributes nearly 29 percent. As with SnPb and SnCu, SAC receives its greatest contribution from the upstream stage, however, at a much higher percentage (96 percent). The use/application stage constitutes nearly all the remaining impacts for SAC. Solder manufacturing and EOL processes contribute small amounts to the overall air particulate impacts.

Air Particulate Impacts by Process Group (Bar Solder)

Table 3-58 lists the air particulate impact scores for each of the processes in the life-cycle of the bar solder. For SAC, silver production is the greatest contributor to total air particulate impacts (84 percent), while tin production is the greatest contributor for the SnPb and SnCu alloys (56 and 69 percent, respectively). Tin production might be expected to have a larger impact as it is the largest proportion of the alloy by composition. Silver, on the other hand, is only a small amount by composition in SAC (3.9 percent by weight); however, its production dominates the air particulate impacts, while tin production is only 12 percent of total impacts. This suggests that silver has much greater air particulate emissions than tin per unit of metal produced.

Table 3-58. Air particulate impacts by life-cycle stage and process group (bar solder)

Life-cycle stage	SnPb		SAC		SnCu	
Process group	Score*	%	Score*	%	Score*	%
UPSTREAM						
Sn production	8.39E-02	56.3	1.78E-01	12.1	1.37E-01	68.9
Pb production	1.33E-03	0.890	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	1.23E+00	83.8	N/A	N/A
Cu production	N/A	N/A	6.57E-05	0.0045	6.44E-05	0.0324
Total	**8.52E-02**	**57.1**	**1.41E+00**	**95.9**	**1.37E-01**	**68.9**
MANUFACTURING						
Solder manufacturing	7.79E-04	0.522	1.19E-03	0.0811	1.18E-03	0.596
Post-industrial recycling	6.16E-03	4.13	1.76E-03	0.1197	3.02E-03	1.52
Total	**6.94E-03**	**4.66**	**2.95E-03**	**0.201**	**4.20E-03**	**2.11**
USE/APPLICATION						
Solder application	5.66E-02	38.0	5.73E-02	3.89	5.73E-02	28.8
Total	**5.66E-02**	**38.0**	**5.73E-02**	**3.89**	**5.73E-02**	**28.8**
END-OF-LIFE						
Landfill	7.25E-06	0.0049	6.34E-06	0.0004	6.30E-06	0.0032
Incineration	-5.17E-06	-0.0035	-4.52E-06	-0.0003	-4.49E-06	-0.0023
Demanufacturing	3.91E-05	0.0262	3.42E-05	0.0023	3.40E-05	0.0171
Cu smelting	3.02E-04	0.203	2.64E-04	0.0180	2.62E-04	0.132
Unregulated	0.00E+00	0.0000	0.00E+00	0.0000	0.00E+00	0.0000
Total	**3.43E-04**	**0.230**	**3.00E-04**	**0.0204**	**2.98E-04**	**0.150**
GRAND TOTAL	**1.49E-01**	**100**	**1.47E+00**	**100**	**1.99E-01**	**100**

*The impact scores are in units of kilograms of particulate matter/1,000 cubic centimeters of solder applied to a printed wiring board.
N/A=not applicable

Emissions from the production of energy consumed during wave solder application contribute about 38 and 29 percent of the total air particulates score for SnPb and SnCu, respectively. The wave application process group for SAC contributes much less on a percentage basis (3.9 percent), although the absolute quantities for all three alloys are very similar, ranging from 0.0566 to 0.0573 kg of particulate matter per functional unit.

The manufacturing stage is a small contributor overall, ranging from 0.20 to 4.7 percent. All three alloys have more impacts from post-industrial recycling than from solder manufacturing itself. This is due to the fact that more secondary SnPb, compared to secondary SAC and SnCu, is used and generated from the post-industrial recycling process. As SAC and SnCu have lower secondary alloy content in the solder manufacturing process, they have lower post-industrial recycling impacts. The higher impacts from post-industrial recycling for SnPb are counter-balanced by the greater upstream impacts for the lead-free alternatives, which have greater virgin content in the alloys.

EOL processes are even smaller contributors to air particulates, accounting for no more than 0.23 percent of the total air particulates impact indicator for any solder alloy. The largest contributions result from smelting processes that recover copper and other valuable metals from waste electronics (percent contributions range from 0.02 to 0.2 percent). The demanufacturing process group that includes electricity generation is the second greatest contributor to EOL impacts, with between 0.0023 and 0.026 percent contribution to total air particulate impacts. Landfilling and incineration are very small contributors to air particulate impacts, and the lack of particulate emissions from unregulated recycling and disposal result in no impacts associated with unregulated recycling and disposal.

Top Contributors to Air Particulate Impacts (Bar Solder)

Table 3-59 presents the specific materials or flows contributing greater than 1 percent to air particulate impacts by solder. The only materials in the inventory that contribute to this impact category are unspecified dust and PM_{10}. As expected from the results above, all the top contributors are from the upstream and use/application stages, or to a lesser degree, from the manufacturing life-cycle stage. Dust from tin production for each alloy is a top contributor.

For SnPb, dust emitted from tin production in the upstream stage contributes about 53 percent of total particulate impacts, and dust from electricity produced for the use/application stage contributes about 18 percent. Dust from electricity generation from post-industrial recycling, as well as the post-industrial recycling process itself, contributes less than 4 percent combined. SAC is dominated by dust from silver production (84 percent), followed by tin production (12 percent), and electricity generation during wave application (4 percent).

Dust as top contributor to SnCu is from tin production (69 percent), electricity generation from wave application (29 percent), and electricity from post-industrial recycling (1 percent). The ME&P inventories are from secondary data sources that do not distinguish whether the particulate matter is emitted from electric power used or directly released during extraction and processing.

Table 3-59. Top contributors to air particulate impacts (bar solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	Upstream	Tin production	Dust (unspecified)	56.3
	Use/application	Electricity generation	Dust (unspecified)	38.0
	Manufacturing	Electricity generation for post-industrial recycling	Dust (unspecified)	2.87
	Manufacturing	Post-Industrial SnPb recycling	Particulate matter (PM-10)	1.09
SAC	Upstream	Silver production	Dust (unspecified)	83.8
	Upstream	Tin production	Dust (unspecified)	12.1
	Use/application	Electricity generation	Dust (unspecified)	3.89
SnCu	Upstream	Tin production	Dust (unspecified)	68.9
	Use/application	Electricity generation	Dust (unspecified)	28.8
	Manufacturing	Electricity generation for post-industrial recycling	Dust (unspecified)	1.02

3.2.8.4 Limitations and uncertainties

For paste solders, the three processes with the greatest contribution to air particulate impacts are electricity generation from solder reflow application and tin production (for all alloys), and silver production (for the lead-free alloys). Similarly, for bar solders, the processes with the greatest contribution are silver production, tin production, and wave application. For the paste solders, sources of uncertainty in the use/application stage inventory have been discussed previously (e.g., 3.2.1.4) and include the following: (1) reflow energy is based on a limited number of data points that cover a wide range, and (2) electricity production data are from a secondary source. Energy consumed during the reflow process is the subject of a sensitivity analysis presented in Section 3.3. For bar solders, the uncertainty in the use stage is related to the secondary data of the electricity production inventory, as described above; however, the wave application data are expected to be a good representation of the process and the same uncertainties described for reflow application of paste solders does not apply.

Uncertainties related to the silver inventory are described in Section 3.2.1.4 and are related to the fact that two of the silver inventories available to the LFSP vary considerably in the magnitude of flows from silver production. Section 3.2.1.4 concludes that although the GaBi data set used in this analysis is considered “good’ by GaBi, and was the preferred inventory for this study, there remains enough uncertainty to perform an additional analysis using the alternate inventory from the DEAM database. Results of the alternate analysis are presented in Section 3.3.

The quality of tin production inventory data is deemed of average reliability and average completeness from IDEMAT (Delft University of Technology), the original source of the data supplied through *Ecobilan* (described in Section 2.2). The data used in the tin production inventory are from data sources dated 1983 and 1989. As a consequence, the tin production data, as used in the LFSP, are considered to be of moderate quality.

The impacts from air particulates are calculated as a direct measure of the inventory, therefore, no direct additional uncertainty is introduced into the results from the characterization calculations. The impact characterization is intended to be based on PM_{10} that is in the respirable range and considered more damaging to the respiratory system than larger particles when considering the effects of particulate matter on human health. Because most of the inventory for this category is catalogued as unspecified dust, it is not known if these are PM_{10} particles. If the dust includes a broader class of particulate emissions, it is likely that the results are somewhat overstated if they are to represent PM_{10} only.

3.2.9 Water Eutrophication Impacts

3.2.9.1 Characterization

Eutrophication (nutrient enrichment) impacts to water are based on the identity and concentrations of eutrophication chemicals released to surface water after treatment. Equivalency factors for eutrophication have been developed assuming nitrogen (N) and phosphorus (P) are the two major limiting nutrients. Therefore, the partial equivalencies are based on the ratio of N to P in the average composition of algae ($C_{106}H_{263}O_{110}N_{16}P$) compared to the reference compound phosphate (PO_4^{3-}) (Heijungs *et al.*, 1992; Lindfors *et al.*, 1995). If the wastewater stream is first sent to a publicly-owned treatment works (POTW), treatment is considered as a separate process, and the impact score would be based on releases from the POTW to surface waters. Impact characterization is based on eutrophication potentials (EP) (Appendix D) and the inventory amount:

$$(IS_{EUTR})_i = (EF_{EP} \times Amt_{EC})_i$$

where:

IS_{EUTR}	equals the impact score for regional water quality impacts from chemical *i* (kg phosphate equivalents) per functional unit;
EF_{EP}	equals the EP equivalency factor for chemical *i* (phosphate equivalents) (Appendix D); and
Amt_{EC}	equals the inventory mass (kg) of chemical *i* per functional unit of eutrophication chemical in a wastewater stream released to surface water after any treatment, if applicable.

3.2.9.2 Paste solder results

Total Water Eutrophication Impacts by Life-Cycle Stage (Paste Solder)

Table 3-60 presents the solder paste results for water eutrophication impacts by life-cycle stage, based on the impact assessment methodology presented above. The table lists the water eutrophication impact scores per functional unit for the life-cycle stages of each solder paste alloy, as well as the percent contribution of each life-cycle stage to the total impacts. Figure 3-21 presents the results in a stacked bar chart.

Table 3-60. Water eutrophication impacts by life-cycle stage (paste solder)

Life-cycle stage	**SnPb**		**SAC**		**BSA**		**SABC**	
	Score*	%	Score*	%	Score*	%	Score*	%
Upstream	1.27E-04	0.104	3.70E-03	3.14	1.72E-03	1.89	2.39E-03	2.04
Manufacturing	1.60E-03	1.31	1.63E-03	1.39	9.32E-04	1.03	1.63E-03	1.40
Use/application	1.20E-01	98.5	1.12E-01	95.4	8.79E-02	97.1	1.13E-01	96.5
End-of-life	9.72E-05	0.0800	8.41E-05	0.0714	1.22E-05	0.0134	8.45E-05	0.0722
Total	**1.22E-01**	**100**	**1.18E-01**	**100**	**9.06E-02**	**100**	**1.17E-01**	**100**

*The impact scores are in units of kilograms phosphate-equivalents/1,000 cubic centimeters of solder paste applied to a printed wiring board.

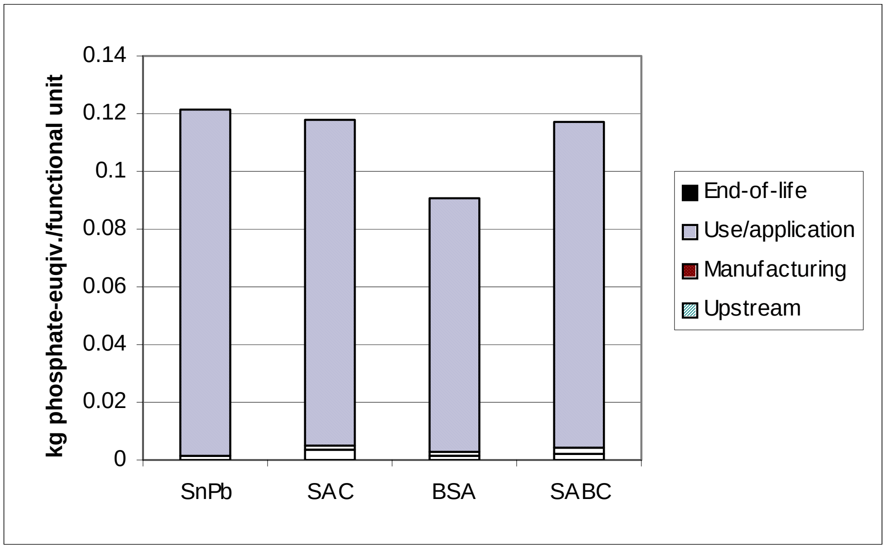


Figure 3-21. Solder Paste Total Life-Cycle Impacts: Water Eutrophication

As shown in the table and figure, SnPb has the greatest impact indicator for water eutrophication at 0.122 kg phosphate-equivalents/functional unit, followed closely by SAC and SABC reflow solder (0.118 and 0.117 kg phosphate-equivalents/functional unit, respectively). BSA, at 0.091 kg phosphate-equivalents/functional unit, has the lowest impact score indicator. While the SnPb water eutrophication indicator is slightly greater than that of SAC or SABC (less than 4 percent), the scores may be indistinguishable given uncertainties in the data.

The use/application life-cycle stage accounts for nearly 95 to 99 percent of total water eutrophication impacts. The second greatest contributing life-cycle stage for SnPb is manufacturing (about 1 percent); for the lead-free alternatives, the second greatest contributing life-cycle stage is the upstream stage (about 2 to 3 percent). The manufacturing stage for the lead-free alternatives contribute about 1 percent each. EOL processes contribute relatively little to total impacts, accounting for 0.08 percent or less of the total water eutrophication impacts for each solder paste.

Water Eutrophication Impacts by Process Group (Paste Solder)

Table 3-61 lists the water eutrophication impacts of each of the processes in the life-cycle of the solder pastes. Releases associated with the generation of the energy required during reflow assembly dominate the water eutrophication impact score for each of the solder alloys.

Compared to the use/application stage, the manufacturing stage is a small contributor overall, with SnPb, SAC, and SABC having nearly the same total manufacturing impacts (approximately 0.0016 kg phosphate-equivalents/functional unit). The impacts from BSA are lower (0.0009 kg phosphate equivalents/functional units).

Despite the similar total manufacturing impacts for SnPb, SAC, and SABC, the distribution of impacts between manufacturing processes differs. SnPb has more impact from post-industrial recycling (0.00113 kg phosphate-equivalents/functional unit) than SAC and SABC (0.000882 and 0.000880 kg phosphate-equivalents/functional unit, respectively). This is due to the fact that more secondary SnPb is used and generated from the post-industrial recycling process. SAC and SABC have lower secondary alloy content in the solder manufacturing, and thus have lower post-industrial recycling impacts. The greater impacts from post-industrial recycling for SnPb are counter-balanced by the greater upstream impacts for the lead-free alternatives that have a larger virgin content in the alloys. See Section 3.2.2.2 for a more complete discussion of this trade-off. Upstream and EOL processes also are both small contributors to the eutrophication impacts. Upstream process impact scores are dominated by the silver production process with the overall impacts ranging from approximately 1 to 3 percent for the lead-free alternatives. By contrast, bismuth production for the BSA alloy contributes about 0.7 percent to the total BSA life-cycle eutrophication impacts.

Table 3-61. Water eutrophication impacts by life-cycle stage and process group (paste solder)

Life-cycle stage	**SnPb**		**SAC**		**BSA**		**SABC**	
Process group	Score*	%	Score*	%	Score*	%	Score*	%
UPSTREAM								
Sn production	6.06E-08	0.00005	8.87E-08	0.0001	4.55E-08	0.00005	8.96E-08	0.0001
Pb production	1.27E-04	0.104	N/A	N/A	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	3.69E-03	3.13	1.10E-03	1.22	2.38E-03	2.03
Cu production	N/A	N/A	5.86E-06	0.0050	N/A	N/A	4.91E-06	0.0042
Bi production	N/A	N/A	N/A	N/A	6.14E-04	0.677	9.28E-06	0.0079
Total	**1.27E-04**	**0.104**	**3.70E-03**	**3.14**	**1.72E-03**	**1.89**	**2.39E-03**	**2.04**
MANUFACTURING								
Solder manufacturing	4.63E-04	0.381	7.50E-04	0.636	4.69E-04	0.518	7.53E-04	0.644
Post-industrial recycling	1.13E-03	0.932	8.82E-04	0.749	4.63E-04	0.511	8.80E-04	0.752
Total	**1.60E-03**	**1.31**	**1.63E-03**	**1.39**	**9.32E-04**	**1.03**	**1.63E-03**	**1.40**
USE/APPLICATION								
Reflow application	1.20E-01	98.5	1.12E-01	95.4	8.79E-02	97.1	1.13E-01	96.5
Total	**1.20E-01**	**98.5**	**1.12E-01**	**95.4**	**8.79E-02**	**97.1**	**1.13E-01**	**96.5**

Table 3-61. Water eutrophication impacts by life-cycle stage and process group (paste solder)

Life-cycle stage	**SnPb**		**SAC**		**BSA**		**SABC**	
Process group	Score*	%	Score*	%	Score*	%	Score*	%
END-OF-LIFE								
Landfill	6.41E-07	0.0005	5.55E-07	0.0005	6.86E-07	0.0008	5.57E-07	0.0005
Incineration	-4.74E-07	-0.0004	-4.10E-07	-0.0003	-5.07E-07	-0.0006	-4.12E-07	-0.0004
Demanufacture	1.18E-05	0.0097	1.02E-05	0.0086	1.20E-05	0.0132	1.02E-05	0.0087
Cu smelting	8.53E-05	0.0702	7.38E-05	0.0626	N/A	N/A	7.41E-05	0.0633
Unregulated	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00
Total	**9.72E-05**	**0.0800**	**8.41E-05**	**0.0714**	**1.22E-05**	**0.0134**	**8.45E-05**	**0.0722**
GRAND TOTAL	**1.22E-01**	**100**	**1.18E-01**	**100**	**9.06E-02**	**100**	**1.17E-01**	**100**

*The impact scores are in units of kilograms phosphate-equivalents/1,000 cubic centimeters of solder paste applied to a printed wiring board.
N/A=not applicable

Top Contributors to Eutrophication Impacts (Paste Solder)

Table 3-62 presents the specific materials or flows contributing at least 1 percent of eutrophication impact scores by solder. The only material that meets this criterion is chemical oxygen demand (COD) in flows from electricity generation processes and from silver production (for the silver-containing alloys). Other flows in the LFSP inventory that contribute to the eutrophication impacts include ammonia/ammonium, phosphate, and nitrate, each contributing less than 1 percent of the overall impacts for a specific solder. As expected from the results above, COD from the use/application stage is the top contributor to total eutrophication impacts, ranging from 94 to 97 percent of total impacts depending on the solder. Flows of COD from silver production contribute from about 1 to 3 percent. The silver extraction and processing inventory is from a secondary data source that does not distinguish whether the eutrophication-causing substances are released from the generation of electric power used or are directly released during extraction and processing.

Table 3-62. Top contributors to water eutrophication impacts (paste solder)

Solder	**Life-Cycle Stage**	**Process**	**Flow**	**% Contribution**
SnPb	Use/application	Electricity generation	COD	97.1
SAC	Use/application	Electricity generation	COD	94.1
	Upstream	Silver production	COD	2.93
BSA	Use/application	Electricity generation	COD	95.7
	Upstream	Silver production	COD	1.14
SABC	Use/application	Electricity generation	COD	95.1
	Upstream	Silver production	COD	1.90

3.2.9.3 Bar solder results

Total Water Eutrophication Impacts by Life-Cycle Stage (Bar Solder)

Table 3-63 presents the bar solder results for water eutrophication impacts by life-cycle stage, based on the impact assessment methodology presented above. The table lists the water eutrophication impact scores per functional unit for the life-cycle stages of each bar solder alloy, as well as the percent contribution of each life-cycle stage to the total impacts. Figure 3-22 presents the results in a stacked bar chart.

Table 3-63. Water eutrophication impacts by life-cycle stage (bar solder)

Life-cycle stage	**SnPb**		**SAC**		**SnCu**	
	Score*	%	Score*	%	Score*	%
Upstream	1.13E-04	0.529	5.49E-03	21.3	9.70E-06	0.047
Manufacturing	2.22E-03	10.4	9.75E-04	3.79	1.35E-03	6.56
Use/application	1.89E-02	88.6	1.92E-02	74.5	1.92E-02	92.9
End-of-life	1.08E-04	0.505	9.45E-05	0.368	9.39E-05	0.455
Total	**2.14E-02**	**100**	**2.57E-02**	**100**	**2.06E-02**	**100**

*The impact scores are in units of kilograms phosphate-equivalents/1,000 cubic centimeters of bar solder applied to a printed wiring board.

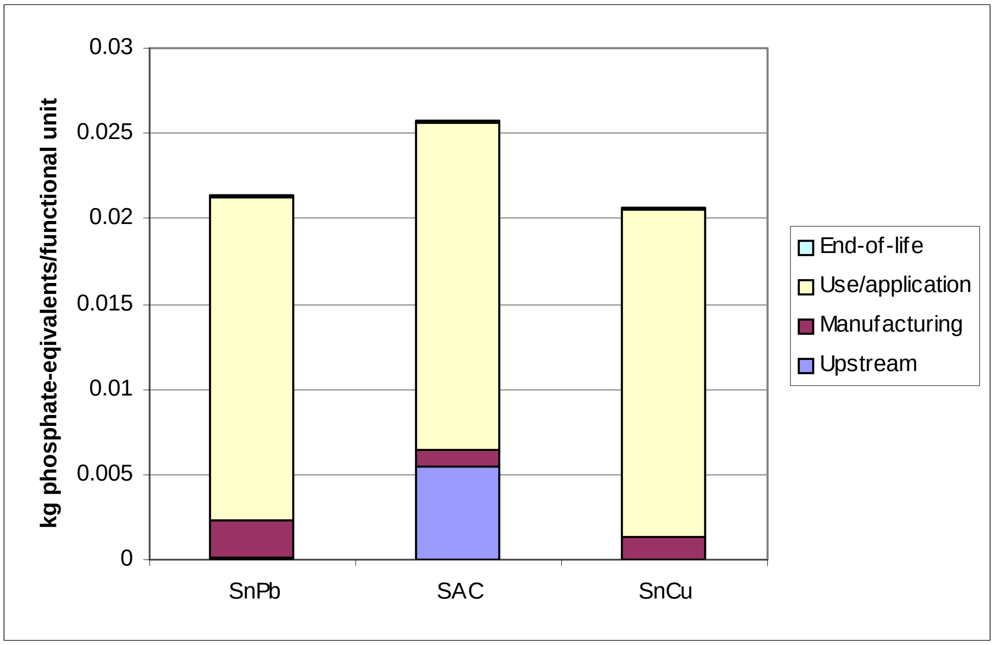


Figure 3-22. Bar Solder Total Life-Cycle Impacts: Water Eutrophication

As shown in the table and figure, SAC has the greatest impact indicator for water eutrophication at 0.0257 kg phosphate-equivalents/functional unit, followed closely by the SnPb and SnCu bar solders at 0.0214 and 0.0206 kg phosphate-equivalents/functional unit, respectively. The use/application life-cycle stage is by far the dominant contributing life-cycle stage, accounting for at least 75 percent of the total water eutrophication impacts of each of the solder alloys and ranging as high as 93 percent for the SnCu alloy. Impacts from upstream processes are significant for the SAC alloy, accounting for nearly 23 percent of the overall impacts, but are not a factor for the non-silver alloys contributing less than one percent of their overall impact scores. The manufacturing life-cycle stage impacts range from roughly 4 percent for SAC up to a high of 10 percent for SnPB. EOL processes contribute relatively little to total impacts, accounting for 0.505 percent or less of the total water eutrophication impacts for each solder type.

Water Eutrophication Impacts by Process Group (Bar Solder)

Table 3-64 lists the water eutrophication impacts of each of the processes in the life-cycle of the bar solder alloys. Releases associated with the generation of the energy required during wave assembly dominate the water eutrophication impact score for each of the solder alloys.

As mentioned previously, SAC had the highest eutrophication impact score, nearly 20 percent higher than both the SnPb and SnCu solders. The difference is due mostly to the impacts associated with the mining and extraction of the silver content in the SAC alloy, which comprises only 3.9 percent of the alloy. Impacts from silver mining are a minimum of 3 orders of magnitude higher than the impacts associated with the mining of the other metals, including tin, which makes up 95.5 percent of the solder alloy.

As seen with the paste solders, impacts associated with the use/application stage once again dominate the overall water eutrophication impacts, ranging from 89 to 93 percent of the overall impacts for the non-silver alloys. These impacts result from the generation of energy required for the wave application of solder to PWBs during the assembly process. Despite having nearly identical impact scores (0.0189- 0.0192 kg phosphate equivalent per 1,000 cubic centimeters of solder) for all of the alloys, impacts from wave soldering account for only 75 percent of the eutrophication impacts for the SAC alloy, again due to the additional impacts from the mining and extraction of silver.

For the non-silver containing alloys of SnPb and SnCu, the manufacturing life-cycle stage processes make up the majority of the remainder of the impacts. Post-industrial recycling of the solder makes the only other significant contribution to eutrophication impacts, ranging from 4.4 to 9 percent. Solder manufacturing accounts for no more than 2.1 percent of the overall eutrophication impacts, while the other remaining life-cycle processes make minimal overall contributions to eutrophication impacts.

Table 3-64. Water eutrophication impacts by life-cycle stage and process group (bar solder)

Life-cycle stage	**SnPb**		**SAC**		**SnCu**	
Process group	Score*	%	Score*	%	Score*	%
UPSTREAM						
Sn production	5.89E-08	0.0003	1.25E-07	0.0005	9.63E-08	0.0005
Pb production	1.13E-04	0.529	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	5.48E-03	21.3	N/A	N/A
Cu production	N/A	N/A	9.79E-06	0.0381	9.61E-06	0.0466
Total	**1.13E-04**	**0.529**	**5.49E-03**	**21.3**	**9.70E-06**	**0.0**
MANUFACTURING						
Solder manufacturing	3.09E-04	1.44	4.41E-04	1.71	4.38E-04	2.12
Post-industrial recycling	1.91E-03	8.92	5.34E-04	2.08	9.15E-04	4.44
Total	**2.22E-03**	**10.4**	**9.75E-04**	**3.79**	**1.35E-03**	**6.56**
USE/APPLICATION						
Wave application	1.89E-02	88.6	1.92E-02	74.5	1.92E-02	92.9
Total	**1.89E-02**	**88.6**	**1.92E-02**	**74.5**	**1.92E-02**	**92.9**
END-OF-LIFE						
Landfill	7.12E-07	0.0033	6.23E-07	0.0024	6.19E-07	0.0030
Incineration	-4.99E-07	-0.0023	-4.37E-07	-0.0017	-4.34E-07	-0.0021
Demanufacture	1.31E-05	0.0611	1.14E-05	0.0445	1.14E-05	0.0551
Cu smelting	9.47E-05	0.443	8.29E-05	0.322	8.23E-05	0.399
Unregulated	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00
Total	**1.08E-04**	**0.51**	**9.45E-05**	**0.368**	**9.39E-05**	**0.46**
GRAND TOTAL	**2.14E-02**	**100**	**2.57E-02**	**100**	**2.06E-02**	**100**

*The impact scores are in units of kilograms phosphate-equivalents/1,000 cubic centimeters of bar solder applied to a printed wiring board.
N/A=not applicable

Top Contributors to Eutrophication Impacts (Bar Solder)

Table 3-65 presents the specific materials or flows contributing at least 1 percent of eutrophication impact scores by bar solder alloy. Ammonia and COD are the only materials in the life-cycle inventory that meet this criterion.

COD releases during the generation of electricity used within the life-cycle of bar solders are the top contributors to water eutrophication. Electricity generation for the use/application of solder during the wave assembly process results in the largest COD loading, contributing from 74 to 92 percent of the water eutrophication impact score. The generation of electricity for other uses, such as post-industrial recycling and manufacturing of the solder alloy also contribute to the overall COD releases (between 2.8 and 7.7 percent to the total impacts).

Flows of COD from silver production contribute from nearly 20 percent for the SAC alloy; however, the silver extraction and processing inventory is from a secondary data source that does not distinguish whether the eutrophication-causing substances are released from the generation of electric power used or directly released during extraction and processing.

Other flows in the LFSP inventory that contribute to the eutrophication impacts include ammonia/ammonium, phosphate, and nitrate, each contributing less than one percent of the overall impacts for any solder. Ammonia released during the post-industrial recycling of the SnPb and SnCu alloys accounts for a small percentage of the overall eutrophication scores for each alloy.

Table 3-65. Top contributors to water eutrophication impacts (bar solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	Use/application	Electricity generation	COD	87.4
	Manufacturing	Electricity generation for post-industrial recycling	COD	6.61
	Manufacturing	Post-industrial SnPb recycling	Ammonia	2.06
	Manufacturing	SnPb bar solder manufacturing	COD	1.04
SAC	Use/application	Electricity generation	COD	73.5
	Upstream	Silver production	COD	19.9
	Manufacturing	Electricity generation for post-industrial recycling	COD	1.51
	Manufacturing	Electricity generation for solder manufacturing	COD	1.30
SnCu	Use/application	Electricity generation	COD	91.6
	Manufacturing	Electricity generation for post-industrial recycling	COD	3.24
	Manufacturing	Electricity generation for solder manufacturing	COD	1.61
	Manufacturing	Post-industrial SnCu recycling	Ammonia	1.01

3.2.9.4 Limitations and uncertainties

The major contributors to energy impacts are from electricity generation used during the use/application stage (particularly for paste solders) and from upstream materials extraction processes (particularly for SAC bar solder). Similar to the discussion in Section 3.2.1, where electricity generation for reflow application is concerned, the same uncertainties apply: (1) the number of data points used to estimate reflow electricity consumption are limited and cover a large range, and (2) electricity production data are from a secondary source. With regard to the first source of uncertainty, the amount of electricity consumed during reflow was measured during reflow testing conducted by the LFSP. These are primary data collected under controlled conditions to meet the goals and objectives of this study and represent good high and low estimates of wave electricity consumption; however, because the value used in this baseline analysis is averaged from a limited amount of data (two data points for each solder), a sensitivity analysis was performed using the high and low values (see Section 3.3). On the other hand, uncertainties from the use of secondary data for electricity generation are not considered large enough to warrant any further analysis.

For wave application results, primary data also were collected for the solder application process through a controlled testing protocol. Although data from only one test run were used, these data were compared to other known testing data and are expected to be representative of typical wave operations, thus introducing little uncertainty. The use of the secondary data for the electricity generation data was discussed above.

Uncertainty in the eutrophication results also is derived from the impact assessment methodology. Eutrophication impacts are calculated from the mass of a chemical released directly to surface water and the chemical's EP. The EP is a partial equivalency factor derived from the ratio of nitrogen and phosphorus in the average composition of algae compared to the reference compound phosphate. As a partial equivalency approach, only a subset of substances can be converted into equivalency factors, which is a limitation of this LCIA methodology. The methodology, however, does take into account nitrogen and phosphorus, which are two major limiting nutrients of importance to eutrophication.

3.2.10 Water Quality Impacts

3.2.10.1 Characterization

Water quality impacts are characterized as surface water impacts due to releases of wastes causing oxygen depletion and increased turbidity. Two water quality impact scores are calculated based on the BOD and TSS in the wastewater streams released to surface water. The impact scores are based on releases to surface water following any treatment. Using a loading characterization approach, impact characterization is based on the amount of BOD and TSS in a wastewater stream. The water quality score equations for each are presented below:

$$(IS_{BOD})_i = (Amt_{BOD})_i$$

and

$$(IS_{TSS})_i = (Amt_{TSS})_i$$

where:

IS_{BOD}	equals the impact score for BOD water quality impacts for waste stream *i* (kg) per functional unit;
Amt_{BOD}	equals the inventory amount of BOD in wastewater stream *i* released to surface waters (kg) per functional unit;
IS_{TSS}	equals the impact score for TSS water quality impacts for waste stream *i* (kg) per functional unit; and
Amt_{TSS}	equals the inventory amount of TSS in wastewater stream *i* released to surface waters (kg) per functional unit.

3.2.10.2 Paste solder results

Total Water Quality Impacts by Life-Cycle Stage (Paste Solder)

Table 3-66 presents the solder paste results for water quality impacts by life-cycle stage, based on the impact assessment methodology presented in above. This impact category characterized the impacts on water quality based on the mass loading of BOD and total solids released to surface water. The table lists the water quality impact scores per functional unit for the life-cycle stages of each solder paste alloy, as well as the percent contribution of each life-cycle stage to the total impacts. Figure 3-23 presents the results in a stacked bar chart.

Table 3-66. Water quality impacts by life-cycle stage (paste solder)

Life-cycle stage	SnPb		SAC		BSA		SABC	
	Score*	%	Score*	%	Score*	%	Score*	%
Upstream	2.10E-03	1.17	5.82E-02	25.8	3.59E-02	21.9	3.78E-02	18.3
Manufacturing	6.58E-03	3.67	7.70E-03	3.41	3.17E-03	1.94	7.69E-03	3.73
Use/application	1.70E-01	94.7	1.59E-01	70.5	1.25E-01	76.0	1.60E-01	77.6
End-of-life	8.15E-04	0.455	7.05E-04	0.312	1.64E-04	0.100	7.08E-04	0.343
Total	**1.79E-01**	**100**	**2.26E-01**	**100**	**1.64E-01**	**100**	**2.06E-01**	**100**

*The impact scores are in units of kilograms BOD & solids/1,000 cc of solder paste applied to a printed wiring board.

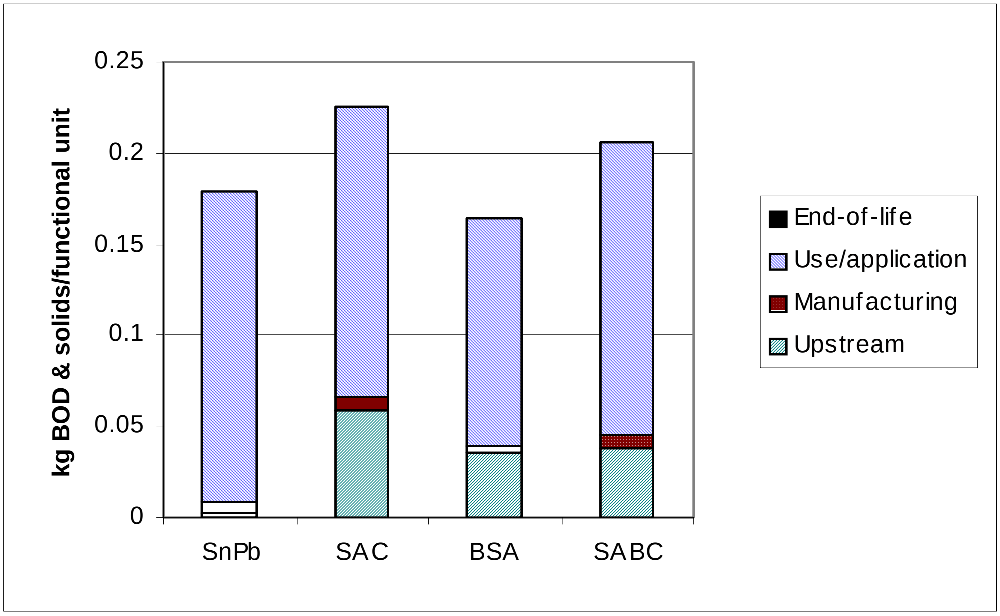


Figure 3-23. Solder Paste Total Life-Cycle Impacts: Water Quality (BOD & Solids)

As shown in the table and figure, SAC solder paste has the greatest impact indicator for water quality (0.226 kg BOD & solids/functional unit); followed by SABC at 0.206 kg BOD & solids/functional unit; SnPb is next with 0.179 kg; and BSA follows with 0.164 BOD & solids/functional unit. Water quality impacts are driven in large part by contributions from the use/application stage, which range from 71 to 95 percent, depending on the solder alloy. While nearly all of the water quality impacts for SnPb result from use/application stage, upstream processes contribute substantially to the water quality, with impacts ranging from 18 to 26 percent. SAC has the greatest upstream impacts at 0.0582 kg, followed by SABC and BSA with 0.378 and 0.359 kg BOD & solids/functional unit each.

Solder manufacturing impacts for the solders contribute between about 1.9 and 3.7 percent of the total life cycle impacts. SAC and SABC have the highest impacts from manufacturing (both at about 0.0077 kg BOD & solids/functional unit), followed closely by

SnPb (0.00658 kg/functional unit). BSA has the least amount of manufacturing impacts (0.00317 kg/functional unit). EOL processes contribute less than 0.5 percent to total impacts for each alloy.

Water Quality Impacts by Process Group (Paste Solder)

Table 3-67 lists the water quality impacts of each of the processes in the life-cycle of the solders. The production of the energy consumed during the reflow assembly of the solders is the single greatest contributor to the water quality impact score. For the lead-free alloys, upstream processes also are significant. Within the upstream stage, silver production for SAC and SABC contribute 26 and 18 percent respectively. As with other impact categories, impacts from silver production are large and disproportionate to the silver content of the alloys (ranging from 1 to 3.9 percent), demonstrating that water quality is affected more from silver by mass than from other metals. BSA water quality impacts are more evenly distributed between bismuth (11.3 percent) and silver (10.6 percent) production processes, despite bismuth comprising a much greater percentage of the solder alloy than silver (57 percent bismuth to 1 percent silver).

The manufacturing stage is a relatively small contributor to the overall water quality impact scores for the solder alloys. Within the manufacturing stage, the post-industrial recycling process is a greater contributor than solder manufacturing. Post-industrial recycling contributes between 1.4 and 3.1 percent, while the solder manufacturing process group contributes 0.7 percent or less for each of the alloys. The distribution of the manufacturing impacts between these two processes is similar to that found in other impact categories discussed earlier.

Likewise, EOL processes do not add substantially to water quality impacts, contributing no more than 0.5 percent of the total water quality impact score. The majority of the impacts come from smelting processes used to recover copper and other valuable metals from waste electronics, contributions range from 0.253 percent to 0.370 percent, except for BSA which does not include copper smelting. There are no BOD or solids emissions assumed in the unregulated recycling and disposal process, and no associated impacts in this impact category.

Table 3-67. Water quality impacts by life-cycle stage and process group (paste solder)

Life-cycle stage	**SnPb**		**SAC**		**BSA**		**SABC**	
Process group	Score*	%	Score*	%	Score*	%	Score*	%
UPSTREAM								
Sn production	8.84E-07	0.0005	1.29E-06	0.0006	6.63E-07	0.0004	1.31E-06	0.0006
Pb production	2.10E-03	1.17	N/A	N/A	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	5.80E-02	25.7	1.73E-02	10.6	3.74E-02	18.1
Cu production	N/A	N/A	2.03E-04	0.0898	N/A	N/A	1.70E-04	0.0823
Bi production	N/A	N/A	N/A	N/A	1.86E-02	11.3	2.81E-04	0.136
Total	**2.10E-03**	**1.17**	**5.82E-02**	**25.8**	**3.59E-02**	**21.9**	**3.78E-02**	**18.3**
MANUFACTURING								
Solder manufacturing	1.03E-03	0.577	1.39E-03	0.616	9.05E-04	0.552	1.40E-03	0.678
Post-industrial recycling	5.55E-03	3.10	6.31E-03	2.79	2.27E-03	1.38	6.29E-03	3.05
Total	**6.58E-03**	**3.67**	**7.70E-03**	**3.41**	**3.17E-03**	**1.936**	**7.69E-03**	**3.73**
USE/APPLICATION								
Reflow application	1.70E-01	94.7	1.59E-01	70.5	1.25E-01	76.0	1.60E-01	77.6
Total	**1.70E-01**	**94.7**	**1.59E-01**	**70.5**	**1.25E-01**	**76.0**	**1.60E-01**	**77.6**
END-OF-LIFE								
Landfill	1.40E-04	0.0780	1.21E-04	0.0535	1.49E-04	0.0911	1.21E-04	0.0589
Incineration	-1.92E-06	-0.0011	-1.66E-06	-0.0007	-2.05E-06	-0.0013	-1.67E-06	-0.0008
Demanufacturing	1.67E-05	0.0093	1.44E-05	0.0064	1.70E-05	0.0104	1.45E-05	0.0070
Cu smelting	6.61E-04	0.369	5.72E-04	0.253	N/A	N/A	5.74E-04	0.278
Unregulated	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00
Total	**8.15E-04**	**0.455**	**7.05E-04**	**0.312**	**1.64E-04**	**0.100**	**7.08E-04**	**0.343**
GRAND TOTAL	**1.79E-01**	**100**	**2.26E-01**	**100**	**1.64E-01**	**100**	**2.06E-01**	**100**

*The impact scores are in units of kilograms BOD & solids/1,000 cc of solder applied to a printed wiring board.
N/A=not applicable

Top Contributors to Water Quality Impacts (Paste Solder)

Table 3-68 presents the specific materials or flows contributing greater than 1 percent of water quality impacts by solder. As expected from the results above, the majority of the top contributors are from the upstream and the use/application stages, with the manufacturing stage also making a contribution. By definition, this section characterizes the water quality based on BOD and total solids, therefore, the flows presented in Table 3-68 are limited to BOD, suspended solids, and dissolved solids. Suspended solids are the majority of water quality impacts for all of the solders, accounting for 89 to 92 percent of the total impact scores, with the largest individual contributions resulting from electricity generation during the use/application stage. Other suspended solids flows include those from the upstream metal production processes as well as heavy fuel oil production. BOD and dissolved solids from electricity production for the use/application stage combine to account for 6 to 8 percent of the water quality impact scores, depending on the solder alloy. Inventories from the extraction and processing of metals, as well as from fuel production, are from secondary data sources that do not distinguish whether the emissions are from electric power used or directly released during extraction, processing, or production.

Table 3-68. Top contributors to water quality impacts (paste solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	Use/application	Electricity generation	Solids (suspended)	86.9
	Use/application	Electricity generation	BOD	4.19
	Use/application	Electricity generation	Solids (dissolved)	3.63
	Manufacturing	Heavy fuel oil (#6) production for post-industrial recycling	Solids (suspended)	1.42
	Upstream	Lead production	Solids (suspended)	1.13
SAC	Use/application	Electricity generation	Solids (suspended)	64.7
	Upstream	Silver production	Solids (suspended)	24.9
	Use/application	Electricity generation	BOD	3.12
	Use/application	Electricity generation	Solids (dissolved)	2.70
BSA	Use/application	Electricity generation	Solids (suspended)	69.8
	Upstream	Bismuth production	Solids (suspended)	11.1
	Upstream	Silver production	Solids (suspended)	10.3
	Use/application	Electricity generation	BOD	3.37
	Use/application	Electricity generation	Solids (dissolved)	2.92
SABC	Use/application	Electricity generation	Solids (suspended)	71.2
	Upstream	Silver production	Solids (suspended)	17.6
	Use/application	Electricity generation	BOD	3.44
	Use/application	Electricity generation	Solids (dissolved)	2.98
	Manufacturing	Heavy fuel oil (#6) production for post-industrial recycling	Solids (suspended)	1.89

3.2.10.3 Bar solder results

Total Water Quality Impacts by Life-Cycle Stage (Bar Solder)

Table 3-69 presents the solder paste results for water quality impacts by life-cycle stage, based on the impact assessment methodology presented above. This impact category characterized the impacts on water quality based on the mass loading of BOD and total solids released to surface water. The table lists the water quality impact scores per functional unit for the life-cycle stages of each solder paste alloy, as well as the percent contribution of each life-cycle stage to the total impacts. Figure 3-24 presents the results in a stacked bar chart.

Table 3-69. Water quality impacts by life-cycle stage (bar solder)

Life-cycle stage	**SnPb**		**SAC**		**SnCu**	
	Score*	%	Score*	%	Score*	%
Upstream	1.88E-03	4.72	8.65E-02	72.2	3.34E-04	0.917
Manufacturing	1.01E-02	25.5	5.37E-03	4.48	8.09E-03	22.2
Use/application	2.69E-02	67.5	2.72E-02	22.7	2.72E-02	74.7
End-of-life	9.06E-04	2.28	7.93E-04	0.662	7.87E-04	2.16
Total	**3.98E-02**	**100**	**1.20E-01**	**100**	**3.64E-02**	**100**

*The impact scores are in units of kilograms BOD & solids/1,000 cc of solder paste applied to a printed wiring board.

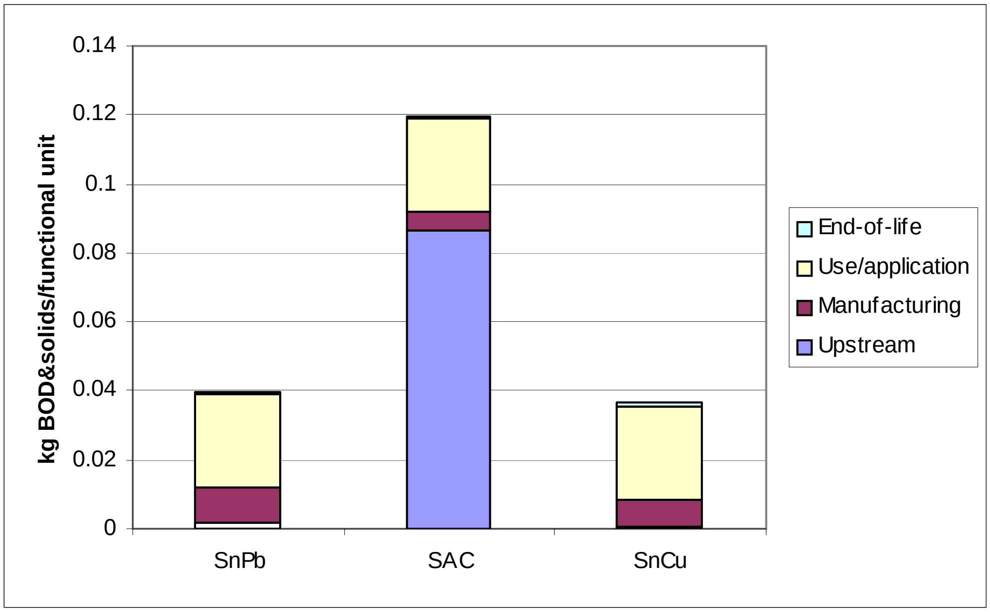


Figure 3-24. Bar Solder Total Life-Cycle Impacts: Water Quality (BOD & Solids)

As shown in the table and figure, SAC solder paste has the greatest impact indicator for water quality (0.226 kg BOD & solids/functional unit); followed by SABC at 0.206 kg BOD & solids/functional unit; SnPb is next with 0.179 kg; and BSA follows with 0.164 BOD & solids/functional unit. Water quality impacts are driven in large part by the contributions from the use/application stage, which range from 71 to 95 percent, depending on the solder alloy. While nearly all of the water quality impacts for SnPb result from use/application stage, upstream processes contribute substantially to the water quality, with impacts ranging from 18 to 26 percent. SAC has the greatest upstream impacts at 0.0582 kg, followed by SABC and BSA with 0.378 and 0.359 kg BOD & solids/functional unit each.

Solder manufacturing impacts for the solders contribute between about 1.9 and 3.7 percent of the total life cycle impacts. SAC and SABC have the highest impacts from manufacturing (both at about 0.0077 kg BOD & solids/functional unit), followed closely by SnPb (0.00658 kg/functional unit). BSA has the least amount of manufacturing impacts

(0.00317 kg/functional unit). EOL processes contribute less than 0.5 percent to total impacts for each alloy.

Water Quality Impacts by Process Group (Bar Solder)

Table 3-70 lists the water quality impacts of each of the processes in the life-cycle of the solders. The production of the energy consumed during the reflow assembly of the solders is the single greatest contributor to the water quality impact score. For the lead-free alloys, upstream processes also are significant. Within the upstream stage, silver production for SAC and SABC contribute 26 and 18 percent, respectively. As with other impact categories, impacts from silver production are large and disproportionate to the silver content of the alloys (ranging from 1 to 3.9 percent), demonstrating that water quality is affected more from silver by mass than from other metals. BSA water quality impacts are more evenly distributed between bismuth (11.3 percent) and silver (10.6 percent) production processes, despite bismuth comprising a much greater percentage of the solder alloy than silver (57 percent bismuth to 1 percent silver).

Table 3-70. Water quality impacts by life-cycle stage and process group (bar solder)

Life-cycle stage	**SnPb**		**SAC**		**SnCu**	
Process group	Score*	%	Score*	%	Score*	%
UPSTREAM						
Sn production	8.59E-07	0.0022	1.82E-06	0.0015	1.40E-06	0.0039
Pb production	1.88E-03	4.72	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	8.61E-02	71.9	N/A	N/A
Cu production	N/A	N/A	3.39E-04	0.283	3.32E-04	0.914
Total	**1.88E-03**	**4.72**	**8.65E-02**	**72.2**	**3.34E-04**	**0.9**
MANUFACTURING						
Solder manufacturing	7.84E-04	1.97	1.55E-03	1.29	1.54E-03	4.22
Post-industrial recycling	9.34E-03	23.5	3.82E-03	3.19	6.55E-03	18.0
Total	**1.01E-02**	**25.5**	**5.37E-03**	**4.48**	**8.09E-03**	**22.2**
USE/APPLICATION						
Wave application	2.69E-02	67.5	2.72E-02	22.7	2.72E-02	74.7
Total	**2.69E-02**	**67.5**	**2.72E-02**	**22.7**	**2.72E-02**	**74.7**
END-OF-LIFE						
Landfill	1.55E-04	0.390	1.36E-04	0.1134	1.35E-04	0.371
Incineration	-2.02E-06	-0.0051	-1.77E-06	-0.0015	-1.75E-06	-0.0048
Demanufacturing	1.85E-05	0.047	1.62E-05	0.0135	1.61E-05	0.044
Cu smelting	7.34E-04	1.85	6.42E-04	0.536	6.38E-04	1.75
Unregulated	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00
Total	**9.06E-04**	**2.28**	**7.93E-04**	**0.662**	**7.87E-04**	**2.16**
GRAND TOTAL	**3.98E-02**	**100**	**1.20E-01**	**100**	**3.64E-02**	**100**

*The impact scores are in units of kilograms BOD & solids/1,000 cc of solder applied to a printed wiring board.
N/A=not applicable

The manufacturing stage is a relatively small contributor to the overall water quality impact scores for the solder alloys. Within the manufacturing stage, the post-industrial recycling process is a greater contributor than solder manufacturing. Post-industrial recycling contributes between 1.4 and 3.1 percent, while the solder manufacturing process group contributes 0.7 percent or less for each of the alloys. The distribution of the manufacturing impacts between these two processes is similar to that found in other impact categories discussed earlier.

Likewise, EOL processes do not add substantially to water quality impacts, contributing no more than 0.5 percent of the total water quality impact score. The majority of the impacts come from smelting processes used to recover copper and other valuable metals from waste electronics (contributions range from 0.253 percent to 0.370 percent, except for BSA which does not include copper smelting). There are no BOD or solids emissions assumed in the unregulated recycling and disposal process, and no associated impacts in this impact category.

Top Contributors to Water Quality Impacts (Bar Solder)

Table 3-71 presents the specific materials or flows contributing greater than 1 percent of water quality impacts by solder. As expected from the results above, the majority of the top contributors are from the upstream and the use/application stages, with the manufacturing stage also making a contribution. By definition, this section characterizes the water quality based on BOD and total solids, therefore, the flows presented in Table 3-71 are limited to BOD, suspended solids, and dissolved solids. Suspended solids constitute the majority of water quality impacts for all of the solders, accounting for 89 to 92 percent of the total impact scores, with the largest individual contributions resulting from electricity generation during the use/application stage. Other suspended solids flows include those from the upstream metal production processes as well as heavy fuel oil production. BOD and dissolved solids from electricity production for the use/application stage combine to account for 6 to 8 percent of the water quality impact scores, depending on the solder alloy. Inventories from the extraction and processing of metals, as well as from fuel production are from secondary data sources that do not distinguish whether the emissions are from electric power used or directly released during extraction, processing, or production.

Table 3-71. Top contributors to water quality impacts (bar solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	Use/application	Electricity generation	Solids (suspended)	62.0
	Manufacturing	Electricity generation for post-industrial recycling	Solids (suspended)	4.69
	Upstream	Lead production	Solids (suspended)	4.53
	Manufacturing	Post-Industrial SnPb recycling	Solids (suspended)	3.23
	Use/application	Electricity generation	BOD	2.99
	Use/application	Electricity generation	Solids (dissolved)	2.59
	Manufacturing	Post-Industrial SnPb recycling	BOD	2.46
	End-of-life	Heavy fuel oil #6 production for Cu smelting	Solids (suspended)	1.37
SAC	Upstream	Silver production	Solids (suspended)	69.8
	Use/application	Electricity generation	Solids (suspended)	20.8
	Manufacturing	Heavy fuel oil #6 post-industrial recycling	Solids (suspended)	1.98
	Upstream	Silver production	BOD	1.18
	Use/application	Electricity generation	BOD	1.00
SnCu	Use/application	Electricity generation	Solids (suspended)	68.5
	Manufacturing	Heavy fuel oil #6 post-industrial recycling	Solids (suspended)	11.2
	Use/application	Electricity generation	BOD	3.31
	Use/application	Electricity generation	Solids (dissolved)	2.86
	Manufacturing	Electricity generation for post-industrial recycling	Solids (suspended)	2.42
	Manufacturing	LPG production for solder manufacturing	Solids (suspended)	2.04
	Manufacturing	Post-industrial SnCu recycling	Solids (suspended)	1.67
	End-of-life	Heavy fuel oil #6 production for Cu smelting	Solids (suspended)	1.30
	Manufacturing	Post-industrial SnCu recycling	BOD	1.27
	Manufacturing	Electricity generation for solder manufacturing	Solids (suspended)	1.21

3.2.10.4 Limitations and uncertainties

The processes that contribute the greatest to the water quality impacts are electricity generation for the reflow application of solder, as well as the upstream metal production processes for the lead-free alloys. Sources of uncertainty in the use/application stage inventory were discussed in Section 3.2.2.1 and include the following: (1) reflow energy is based on a limited number of data points that cover a wide range, and (2) electricity production data are from a secondary source. Energy consumed during the reflow process is the subject of a sensitivity analysis presented in Section 3.3, but uncertainties in the electricity generation inventory were not considered significant. For a more detailed discussion, see Section 3.2.2.1.

Uncertainties related to the silver inventory are described in Section 3.2.2 and have to do with the fact that two alternate silver inventories available to the LFSP vary considerably in the magnitude of flows from silver production. Section 3.2.2 concludes that although the GaBi data set used in this analysis is considered “good” by GaBi, there remains enough uncertainty to perform an additional analysis using the alternate inventory from the DEAM database. Results of the alternate analysis are presented in Section 3.3.

Tin production inventory data quality is deemed of average reliability and average completeness from IDEMAT (Delft University of Technology), the original source of the data supplied through *Ecobilan* (described in Section 2.2). The data used in the tin production inventory are from data sources dated 1983 and 1989. As a consequence, the tin production data, as used in the LFSP, are considered to be of moderate quality.

Uncertainty in the water quality results is derived from the impact assessment methodology. Water quality impacts are calculated using a loading approach based on the mass of BOD and total solids released directly to surface water; therefore, these results are sensitive to the quality of the inventory data, which are discussed above.

3.2.11 Occupational Human Health Impacts

This section presents the LCIA characterization methodology and the LCIA results for the occupational human health impact category; however, some of the discussions relate to all of the toxicity impact categories in general (e.g., occupational human health, public human health, and ecotoxicity). The occupational human health impact results presented in this section include two impact categories: occupational non-cancer impacts and occupational cancer impacts. The results for these categories are provided within each of the subsections below.

3.2.11.1 Characterization

Potential Human Health Impacts

Human health impacts are defined in the context of life-cycle assessment as relative measures of potential adverse health effects to humans. Human health impact categories included in the scope of this LFSP LCA are chronic (repeated dose) effects, including non-carcinogenic and carcinogenic effects. Chronic human health effects to both workers and the public are considered. This section presents the potential occupational health impacts, and Section 3.2.12 presents the potential public health impacts. It was assumed that there is no direct consumer contact with the solder on PWBs, therefore, quantitative measures of consumer impacts are not included in the LCIA methodology.

The chemical characteristic that classifies inventory items to the human health effects (and ecotoxicity) categories is toxicity. Toxic chemicals were identified by searching lists of toxic chemicals (e.g., Toxic Release Inventory [TRI]) and, if needed, toxicity databases (e.g., Hazardous Substances Data Bank [HSDB]), and Registry of Toxic Effects of Chemical Substances (RTECS), and other literature (see Appendix E). The review was done by the DfE Workgroup for the DfE Computer Display Project (Socolof *et al.*, 2001), and remains applicable to the LFSP. Several materials in the LFSP inventory were excluded from the toxic list if they were generally accepted as non-toxic. The EPA DfE Workgroup also reviewed the list of chemicals that were included in this project as potentially toxic. The list of potentially toxic chemicals is provided in Appendix E, and chemicals that were excluded from the toxic list that appear in the LFSP inventory also are presented in Appendix E.

Human (and ecological) toxicity impact scores are calculated based on a chemical scoring method modified from the CHEMS-1 that is found in Swanson *et al.* (1997). To calculate impact scores, chemical-specific inventory data are required. Any chemical that is assumed to be potentially toxic is given a toxicity impact score. This involves collecting toxicity data (described in Appendix E). If toxicity data are unavailable for a chemical, a mean default toxicity score is given. This is described in detail below. Ecological toxicity is presented in Section 3.2.13.

Chronic human health effects are potential human health effects occurring from repeated exposure to toxic agents over a relatively long period of time (i.e., years). These effects could include carcinogenicity, reproductive toxicity, developmental effects, neurotoxicity, immunotoxicity, behavioral effects, sensitization, radiation effects, and chronic effects to other specific organs or body systems (e.g., blood, cardiovascular, respiratory, kidney and liver effects). Impact categories for chronic health effects are divided into cancer and non-cancer effects for both worker and public impacts. Occupational impact scores are based on inventory inputs; public impact scores are based on inventory outputs.

This section addresses chronic occupational health effects, which refer to potential health effects to workers, including cancer, from long-term repeated exposure to toxic or carcinogenic agents in an occupational setting. For possible occupational impacts, the identity and amounts of materials/constituents as input to a process are used. The inputs represent potential exposures. It could be assumed that a worker would continue to work at a facility and incur exposures over time, however, the inventory is based on manufacturing one unit volume of solder as applied to a particular PWB design and does not truly represent chronic exposure; therefore, the chronic health effects impact score is more of a ranking of the potential of a chemical to cause chronic effects than a prediction of actual effects.

Chronic occupational health effects scores are based on the identity of toxic chemicals (or chemical ingredients) found in inputs from all of the life-cycle stages. The distinction between pure chemicals and mixtures is made, if possible, by specifying component ingredients of mixtures in the inventory.

The chronic human health impact scores are calculated using hazard values (HVs) for carcinogenic and non-carcinogenic effects. Calculation of the occupational non-cancer and cancer HVs are described below, and the public non-cancer and cancer HV calculations are described in Section 3.2.12.1. Appendix H provides example calculations of toxicity impacts for two sample chemicals.

Occupational Human Health Characterization: Non-Cancer

The non-carcinogen HV is based on either no-observed-adverse-effect levels (NOAELs) or lowest-observed-adverse-effect levels (LOAELs). The non-carcinogen HV is the greater of the oral and inhalation HV:

$$\textit{inhalation}: \quad (HV_{NC_{inhalation}})_i = \frac{1/(inhal\ NOAEL_i)}{1/(inhal\ NOAEL_{mean})}$$

$$\textit{oral}: \quad (HV_{NC_{oral}})_i = \frac{1/(oral\ NOAEL_i)}{1/(oral\ NOAEL_{mean})}$$

where:

$HV_{NC\ oral}$	equals the non-carcinogen oral hazard value for chemical *i* (unitless);
$oral\ NOAEL_{i}$	equals the oral NOAEL for chemical *i* (mg/kg-day);
$oral\ NOAEL_{mean}$	equals the geometric mean oral NOAEL of all available oral NOAELs (Appendix E) [12.6 mg/kg-day];
$HV_{NC\ inhalation}$	equals the non-carcinogen inhalation hazard value for chemical *i* (unitless);
$inhal\ NOAEL_{i}$	equals the inhalation NOAEL for chemical *i* (mg/m^3); and
$inhal\ NOAEL_{mean}$	equals the geometric mean inhalation NOAEL of all available inhalation NOAELs (Appendix E) [68.7 mg/m^3].

The oral and inhalation NOAEL mean values are the geometric means of a set of chemical data presented in Appendix E. If LOAEL data are available, instead of NOAEL data, the LOAEL, divided by 10, is used to substitute for the NOAEL. The most sensitive endpoint is used if there are multiple data for one chemical.

The non-carcinogen HVs for a particular chemical are multiplied by the applicable inventory input to calculate the impact score for non-cancer effects:

$$(IS_{CHO\text{-}NC})_i = (HV_{NC}\ x\ Amt_{TCinput})_i$$

where:

$IS_{CHO\text{-}NC}$	equals the impact score for chronic occupational non-cancer health effects for chemical *i* (kg noncancer-toxequivalent) per functional unit;
HV_{NC}	equals the hazard value for chronic non-cancer effects for chemical *i*; and
$Amt_{TC\ input}$	equals the amount of toxic inventory input (kg) per functional unit for chemical *i*.

Occupational Human Health Characterization: Cancer

The cancer HV uses cancer slope factors or cancer weight of evidence (WOE) classifications assigned by EPA or the International Agency for Research on Cancer (IARC). If both an oral and inhalation slope factor exist, the slope factor representing the larger hazard is chosen; thus, given that there is a cancer slope factor (SF) for a chemical, the cancer HV for chronic occupational health effects is the greater of the following:

$$oral: \quad (HV_{CA_{oral}})_i = \frac{oral\ SF_i}{oral\ SF_{mean}}$$

$$inhalation: \quad (HV_{CA_{inhalation}})_i = \frac{inhalation\ SF_i}{inhalation\ SF_{mean}}$$

where:

$HV_{CA\ oral}$ equals the cancer oral hazard value for chemical *i* (unitless);
$oral\ SF_i$ equals the cancer oral slope factor for chemical *i* (mg/kg-day)$^{-1}$;
$oral\ SF_{mean}$ equals the geometric mean cancer slope factor of all available slope factors (Appendix E) [0.71 (mg/kg-day)$^{-1}$];
$HV_{CA\ inhalation}$ equals the cancer inhalation hazard value for chemical *i* (unitless);
$inhalation\ SF_i$ equals the cancer inhalation slope factor for chemical *i* (mg/kg-day)$^{-1}$; and
$inhalation\ SF_{mean}$ equals the geometric mean cancer inhalation slope factor of all available inhalation slope factors (Appendix E) [1.70 (mg/kg-day)$^{-1}$].

The oral and inhalation slope factor mean values are the geometric means of a set of chemical data presented in Appendix E.

Where no slope factor is available for a chemical, but there is a WOE classification, the WOE is used to designate default hazard values as follows: EPA WOE Groups D (not classifiable) and E (non-carcinogen) and IARC Groups 3 (not classifiable) and 4 (probably not carcinogenic) are given a hazard value of zero. All other WOE classifications (known, probable, and possible human carcinogen) are given a default HV of 1 (representative of a mean slope factor) (Table 3-72). Similarly, materials for which no cancer data exist, but are designated as potentially toxic, are also given a default value of 1.

Table 3-72. Hazard values for carcinogenicity WOE if no slope factor is available

EPA classification	IARC classification	Description	Hazard value
Group A	Group 1	Known human carcinogen	1
Group B1	Group 2A	Probable human carcinogen (limited human data)	1
Group B2	N/A	Probable human carcinogen (from animal data)	1
Group C	Group 2B	Possible human carcinogen	1
Group D	Group 3	Not classifiable	0
Group E	Group 4	Non-carcinogenic or probably not carcinogenic	0

N/A=not applicable

The cancer HV for a particular chemical, whether it is from a slope factor or WOE, is then multiplied by the applicable inventory amount to calculate the impact score for cancer effects:

$$(IS_{CHO\text{-}CA})_i = (HV_{CA}\ x\ Amt_{TCinput})_i$$

where:

$IS_{CHO\text{-}CA}$	equals the impact score for chronic occupational cancer health effects for chemical i (kg cancertox-equivalents) per functional unit;
HV_{CA}	equals the hazard value for carcinogenicity for chemical i; and
$Amt_{TC\ input}$	equals the amount of toxic inventory input (kg) per functional unit for chemical i.

3.2.11.2 Paste solder results

Total Occupational Impacts by Life-Cycle Stage (Paste Solder)

Table 3-73 presents the paste solder results for occupational *non-cancer* impacts by life-cycle stage, based on the impact assessment methodology presented above. The table below lists the occupational non-cancer impact scores per functional unit for the life-cycle stages of each solder paste alloy, as well as the percent contribution of each life-cycle stage to the total impacts. Figure 3-25 shows the results in a stacked bar chart.

Table 3-73. Occupational non-cancer impacts by life-cycle stage (paste solder)

Life-cycle stage	**SnPb**		**SAC**		**BSA**		**SABC**	
	Score*	%	Score*	%	Score*	%	Score*	%
Upstream	6.03E+00	0.0011	9.59E+00	0.118	5.24E+00	0.224	9.29E+00	0.177
Manufacturing	2.03E+05	36.2	2.84E+03	35.0	7.31E+02	31.3	1.83E+03	34.9
Use/application	1.75E+05	31.2	2.59E+03	31.9	7.95E+02	34.0	1.69E+03	32.1
End-of-life	1.82E+05	32.6	2.67E+03	32.9	8.05E+02	34.4	1.72E+03	32.8
Total	**5.60E+05**	**100**	**8.12E+03**	**100**	**2.34E+03**	**100**	**5.25E+03**	**100**

*The impact scores are in units of kilograms noncancertox-equivalents/1,000 cc of solder applied to a printed wiring board.

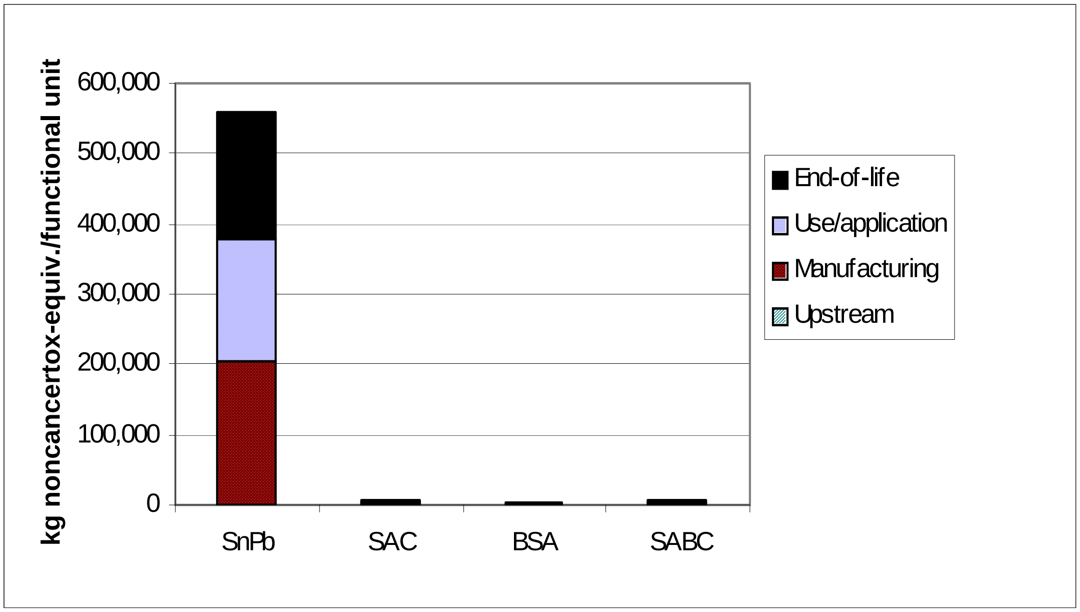


Figure 3-25. Solder Paste Total Life-Cycle Impacts: Occupational Non-Cancer

Occupational impact scores are based on the potential toxicity of material *inputs* to each process. This characterization method does not necessarily indicate where actual exposure is occurring; instead, it uses the inputs of potentially toxic materials as surrogates for exposure. While this methodology introduces some uncertainties into the occupational health impact results, discussed further below, it is an improvement over former LCIA methodologies that do not evaluate occupational health impacts.

As shown in the figure, the occupational non-cancer impact score for SnPb (560,000 kg noncancertox-equivalents/functional unit) is far greater than the scores for other solder alloys (ranging from 2,340 to 8,120 kg noncancertox-equivalents/functional unit). Because SnPb has a higher toxicity compared to the other alloys, its impacts are larger. Note that the HVs of the solders are assumed to be the weighted averages of the HVs of the individual metals and fluxes (when applicable) that make up the alloys.

Three life-cycle stages largely contribute to total impacts, regardless of the solder type: manufacturing, use/application, and EOL. The EOL stage (34.4 percent) was the largest contributor for BSA, slightly exceeding the contributions of the use/application stage (34.0 percent) and manufacturing stage (31.3 percent). For the remaining alloys—SnPb, SAC, and SABC—the solder manufacturing stage accounts for the largest portion of the total occupational non-cancer impacts score, with values ranging from 35 to 36 percent; however, both the EOL and use/application stages also make substantial contributions to the impact score, accounting for a minimum of 31 percent of the overall scores each. For each of the paste solder alloys, the upstream life-cycle stages did not contribute significantly, accounting for less than 0.3 percent of the occupational non-cancer life-cycle impacts.

To help put the scores for occupational non-cancer impacts in perspective, the occupational non-cancer toxicity score associated with using enough electricity to power a 60-watt bulb for one year is 20,677 kg noncancertox-equivalents. The difference between the SnPb and SAC results presented above (i.e., 552,000 kg noncancertox-equivalents) is equivalent to the toxicity impacts associated with continuously running a 60-watt bulb for approximately 27 years. The differences among the lead-free alloys are much smaller; SAC as compared to BSA is equivalent to running a 60-watt bulb for 143 days, which represents a greater difference than many of the other impact categories when compared to electricity used to power a lightbulb. Most of the other impact categories have relative differences on the order of operating a lightbulb for hours to days. These results could indicate either that there are fewer toxic materials used in electricity generation than are used in the solder life-cycle or that the quantities of toxic materials are much greater in the solder life-cycles than for electricity to power a lightbulb.

Table 3-74 presents the solder paste results for occupational human health *cancer* impacts by life-cycle stage, based on the impact assessment methodology presented above. The table lists the occupational cancer impact scores per functional unit for the life-cycle stages of each solder paste, as well as the percent contribution of each life-cycle stage to the total impacts. Figure 3-26 presents the results in a stacked bar chart.

Table 3-74. Occupational cancer impacts by life-cycle stage (paste solder)

Life-cycle stage	**SnPb**		**SAC**		**BSA**		**SABC**	
	Score*	%	Score*	%	Score*	%	Score*	%
Upstream	6.03E+00	7.90	9.43E+00	13.1	5.18E+00	8.17	9.18E+00	12.7
Manufacturing	2.07E+01	27.2	1.79E+01	24.8	1.75E+01	27.6	1.80E+01	24.9
Use/application	4.14E+01	54.3	3.80E+01	52.8	3.27E+01	51.6	3.83E+01	52.9
End-of-life	8.11E+00	10.6	6.71E+00	9.31	7.98E+00	12.6	6.84E+00	9.45
Total	**7.62E+01**	**100**	**7.20E+01**	**100**	**6.34E+01**	**100**	**7.23E+01**	**100**

*The impact scores are in units of kilograms cancertox-equivalents/1,000 cc of solder paste applied to a printed wiring board.

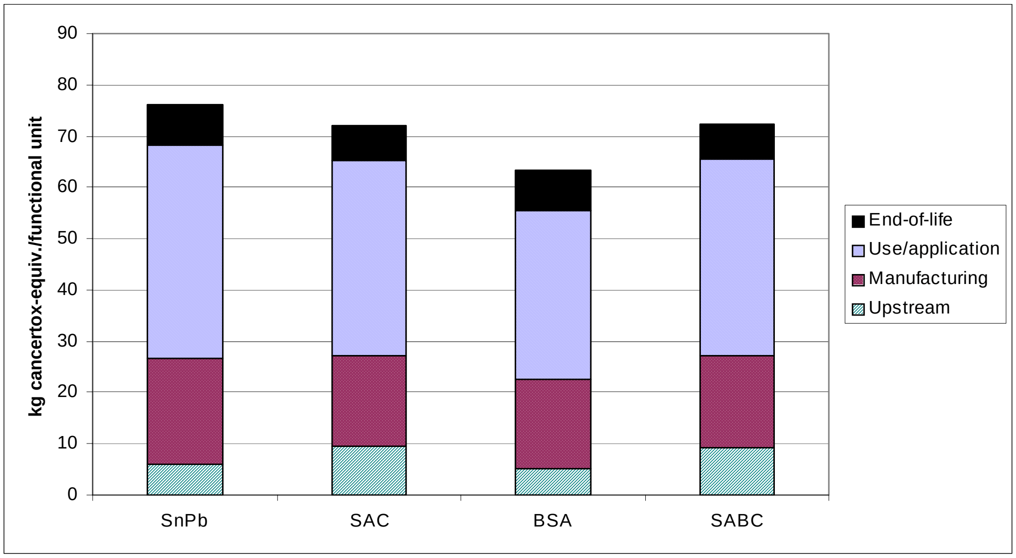


Figure 3-26. Solder Paste Total Life-Cycle Impacts: Occupational Cancer

As shown in the preceding table and figure, SnPb has the greatest occupational cancer impact score (76.2 kg cancertox-equivalents/functional unit), but its score is not much higher than those for SABC and SAC (72.3 and 72.0 kg cancertox-equivalents/functional unit, respectively). In fact, the results for these three alloys may be indistinguishable given the uncertainties in the data. BSA has the lowest total impact score at 63.4 kg cancertox-equivalents/functional unit.

Unlike several other impact categories previously described, the occupational cancer impacts are not completely dominated by one, or even two, life-cycle stages. For all the solders, the use/application stage is the greatest contributor to total occupational cancer impacts, ranging from 52 to 54 percent; however, the manufacturing stage, as well as the EOL and upstream stages, contribute to a large extent. Potential impacts from the manufacturing stage range from 25 to 28 percent, while EOL stage impacts range from 9 to 13 percent depending on the alloy. The contributions of upstream life-cycle stages range from 8 to 13 percent.

In comparison to the occupational *non-cancer* impacts in which SnPb has substantially greater impacts than the other solders, the total *cancer* impacts are much closer in magnitude to one another. This is primarily due to a lack of carcinogenicity data for the solder metals, and may not be an accurate reflection of the potential occupational cancer impacts of the different alloys. For example, lead is the only solder metal that has been classified as a probable human carcinogen (EPA and IARC carcinogenic WOE classifications of B2 and 2A, respectively); however, since no slope factor is available for lead, it receives the same HV (HV=1, representative of an average HV) as tin and bismuth, two solder metals that have not been classified as to carcinogencity. (Average hazard values are assigned to materials that have not been classified to minimize the bias that typically favors materials with little or no toxicity data.) Identical mass inputs of these metals will receive identical occupational cancer scores, even though their relative carcinogenicity is not known. A lack of carcinogenicity data is one of the major limitations and uncertainties in the occupational cancer characterization method, and is discussed further below.

Occupational Impacts by Process Group (Paste Solder)

Table 3-75 lists the occupational *non-cancer* impacts of each of the process groups in the life-cycle of the solders. As noted above, the manufacturing, use/application, and EOL stages all largely contribute to occupational non-cancer impacts for all of the paste solder alloys. The manufacturing stage is made up of two process groups: solder manufacturing and post-industrial recycling, both of which include the fuel production of any associated fuels used during operation. The impacts from solder manufacturing are greater than post-industrial recycling, accounting for 31 to 36 percent of total impacts for all alloys, compared to less than 0.2 percent for post-industrial recycling. This is because the major contributors to the manufacturing impacts are the metals inputs used in production of the alloys (discussed below under the "*Top Contributors*" section), and the non-cancer hazard values of some of those metals (e.g., lead and silver) are very high. On the other hand, the inputs to the post-industrial recycling processes (e.g., dross inputs, which are outputs from the solder manufacturing process) do not have associated toxicity data to develop a hazard value, so the default hazard value is used, which is far below that of lead and silver. Solder manufacturing is the greatest contributor to occupational non-cancer impacts because it has the greatest quantity of solder inputs, and because occupational impacts are based on the quantity and potential toxicity of those inputs.

The reflow application process group within the use/application stage is comprised of the solder reflow process and associated electricity generation. Use/application impacts for occupational non-cancer, therefore, are from the inputs to the reflow process itself, as well as inputs to the electricity generation process.

Landfilling is the greatest contributor to EOL occupational non-cancer impacts (24 to 25 percent of total impacts) for all of the alloys, followed by incineration (6 to 17 percent of total impacts). Demanufacturing, copper smelting, and unregulated recycling/disposal each contribute approximately 1 percent to the total occupational non-cancer impacts for SnPb, SAC, and SABC. These processes make equal contributions to the impacts of each solder alloy since they were assumed to receive equal amounts of waste electronics and, therefore solder, at EOL. Copper smelting is not included in the BSA EOL model.

Like the solder manufacturing process group discussed above, landfilling and incineration dominate occupational non-cancer health impacts at EOL because these dispositions have the greatest inputs of EOL solder, the toxicity and overall quantity of which contribute to the determination of the overall impact score. Furthermore, the LCIA methodology uses input quantities as surrogates for exposure in lieu of incorporating an exposure model as would be done in a chemical risk assessment. For example, within an alloy life-cycle, at this time most electronics are destined for landfilling (at least 72 percent) as modeled in the LFSP and, as a result, the LCIA methodology assumes most occupational exposure to solders occur during landfilling. As a result, the landfilling impacts dominate EOL within each alloy life-cycle. This occurs despite the fact that there may actually be less true occupational exposure to a landfill worker than to a demanufacuturer or copper smelter worker. Given the screening nature of the LCIA occupational impact category method, the process with the greatest quantities of potentially toxic materials would tend to have the greatest impacts for a given set of similar materials. For this reason, the scores for demanufacturing and unregulated recycling/disposal are identical because the LFSP model assumes that equal amounts of EOL solder go to both those dispositions. No mass is assumed to be lost between demanufacturing inputs and copper smelting inputs. The occupational non-cancer impacts from demanufacturing and copper smelting, therefore, are the same because they have the same mass of solder inputs.

Table 3-75. Occupational non-cancer impacts by life-cycle stage and process group (paste solder)

Life-cycle stage	**SnPb**		**SAC**		**BSA**		**SABC**	
Process group	Score*	%	Score*	%	Score*	%	Score*	%
UPSTREAM								
Sn production	5.81E+00	0.0010	8.50E+00	0.105	4.35E+00	0.186	8.58E+00	0.163
Pb production	2.25E-01	0.00004	N/A	N/A	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	1.09E+00	0.0134	3.25E-01	0.0139	7.01E-01	0.0133
Cu production	N/A	N/A	3.80E-03	0.00005	N/A	N/A	3.18E-03	0.0001
Bi production	N/A	N/A	N/A	N/A	5.62E-01	0.0240	8.50E-03	0.0002
Total	**6.03E+00**	**0.0011**	**9.59E+00**	**0.118**	**5.24E+00**	**0.224**	**9.29E+00**	**0.177**
MANUFACTURING								
Solder manufacturing	2.03E+05	36.2	2.83E+03	34.9	7.27E+02	31.1	1.83E+03	34.8
Post-industrial recycling	1.07E+01	0.002	8.79E+00	0.108	4.38E+00	0.187	8.77E+00	0.167
Total	**2.03E+05**	**36.2**	**2.84E+03**	**35.0**	**7.31E+02**	**31.3**	**1.83E+03**	**34.9**
USE/APPLICATION								
Reflow application	1.75E+05	31.2	2.59E+03	31.9	7.95E+02	34.0	1.69E+03	32.1
Total	**1.75E+05**	**31.2**	**2.59E+03**	**31.9**	**7.95E+02**	**34.0**	**1.69E+03**	**32.1**
END-OF-LIFE								
Landfill	1.26E+05	22.4	1.84E+03	22.7	5.82E+02	24.9	1.19E+03	22.6
Incineration	3.32E+04	5.92	4.86E+02	5.99	1.54E+02	6.57	3.13E+02	5.96
Demanufacturing	7.86E+03	1.40	1.15E+02	1.42	3.47E+01	1.48	7.42E+01	1.41
Cu smelting	7.86E+03	1.40	1.15E+02	1.42	N/A	N/A	7.43E+01	1.42
Unregulated	7.86E+03	1.40	1.15E+02	1.42	3.47E+01	1.48	7.42E+01	1.41
Total	**1.82E+05**	**32.6**	**2.67E+03**	**32.9**	**8.05E+02**	**34.4**	**1.72E+03**	**32.8**
GRAND TOTAL	**5.60E+05**	**100**	**8.12E+03**	**100**	**2.34E+03**	**100**	**5.25E+03**	**100**

*The impact scores are in units of kilograms noncancertox-equivalents/1,000 cc of solder paste applied to a printed wiring board.
N/A=not applicable

Differences in impacts beyond differences in the inventory do arise when evaluating the solder paste alloys against one another. For example, SnPb has the greatest impacts versus the other alloys because the toxicity of lead is greater than the toxicity of the materials in the other alloys. This is discussed in the subsection below.

Upstream occupational non-cancer impacts arise from the inputs to the extraction and processing of the various metals present in the alloys. These impacts are small compared to the total life-cycle impacts. When evaluating the upstream impacts alone, tin production is the greatest contributor to the upstream impacts for all alloys, but is still a small percentage of total life-cycle impacts (e.g., from 0.001 to 0.19 percent). For SAC and SABC, silver production is the second greatest upstream contributor (0.013 percent). For BSA, bismuth production is the second greatest contributor at 0.024 percent, followed by silver at 0.014 percent.

Table 3-76 lists the occupational *cancer* impacts of each of the processes in the life-cycle of the solders. The use/application stage is the greatest contributor to occupational cancer impacts for the solders. The reflow solder process is the only process group within this stage, and the only two inputs modeled in the reflow process are solder paste and electricity. Cancer impacts from the use/application stage, therefore, are based on the carcinogenic potential of the solder paste and any potentially carcinogenic inputs to the electricity generation process. The impacts from the use/application stage alone follow the same trend as the total impacts. That is, SnPb has the greatest occupational cancer impact score (41.4 kg cancertox-equivalents/ functional unit), followed closely by SABC (38.3 kg cancertox-equivalents/functional unit), which is only slightly above SAC (38.0 kg cancertox-equivalents/functional unit). BSA has the lowest impacts from the use/application stage at 32.7 kg cancertox-equivalents/functional unit. BSA impacts are expected to be somewhat lower since less electricity is used for reflowing BSA than for the other alloys, primarily due to BSA’s lower melting temperature.

Within the manufacturing stage, which is the second greatest contributor to occupational impacts, the solder manufacturing process group impacts are greater than the post-industrial process group impacts for all the solders. The solder manufacturing process group accounts for 19 to 25 percent and post-industrial recycling accounts for 3 to 6 percent of total impacts for all alloys.

Within the EOL stage, the landfilling process group is the greatest contributor (about 6 to 9 percent of total impacts), followed by incineration (about 1.7 to 2.4 percent of total impacts). Demanufacturing, copper smelting, and unregulated recycling/disposal are smaller contributors to the total occupational cancer impacts for all alloys (about 0.7 percent or less each). Similar to the occupational non-cancer impacts discussed above, landfilling and incineration dominate impacts for this category because, instead of an exposure model, the impacts are based on the quantity of inputs to each process that have the potential to be toxic (carcinogenic, in this case). The demanufacturing, copper smelting, and unregulated impacts are not all equal, as they were for occupational non-cancer impacts, because other input materials in the fuel production processes weigh into the impact scores. This did not occur for non-cancer impacts because the extremely high non-cancer HVs of some of the solder metals (e.g., lead) overshadowed any impacts from other processes, such as fuel production.

Table 3-76. Occupational cancer impacts by life-cycle stage and process group (paste solder)

Life-cycle stage	**SnPb**		**SAC**		**BSA**		**SABC**	
Process group	Score*	%	Score*	%	Score*	%	Score*	%
UPSTREAM								
Sn production	5.81E+00	7.62	8.50E+00	11.8	4.35E+00	6.87	8.58E+00	11.9
Pb production	2.16E-01	0.284	N/A	N/A	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	9.23E-01	1.28	2.75E-01	0.435	5.94E-01	0.821
Cu production	N/A	N/A	3.77E-03	0.0052	N/A	N/A	3.15E-03	0.0044
Bi production	N/A	N/A	N/A	N/A	5.49E-01	0.866	8.30E-03	0.0115
Total	**6.03E+00**	**7.90**	**9.43E+00**	**13.1**	**5.18E+00**	**8.17**	**9.18E+00**	**12.7**
MANUFACTURING								
Solder manufacturing	1.60E+01	21.1	1.37E+01	19.0	1.56E+01	24.6	1.39E+01	19.2
Post-industrial recycling	4.66E+00	6.12	4.15E+00	5.77	1.91E+00	3.01	4.14E+00	5.72
Total	**2.07E+01**	**27.2**	**1.79E+01**	**24.8**	**1.75E+01**	**27.6**	**1.80E+01**	**24.9**
USE/APPLICATION								
Reflow application	4.14E+01	54.3	3.80E+01	52.8	3.27E+01	51.6	3.83E+01	52.9
Total	**4.14E+01**	**54.3**	**3.80E+01**	**52.8**	**3.27E+01**	**51.6**	**3.83E+01**	**52.9**
END-OF-LIFE								
Landfill	5.48E+00	7.19	4.53E+00	6.29	5.78E+00	9.12	4.62E+00	6.39
Incineration	1.43E+00	1.87	1.18E+00	1.64	1.51E+00	2.38	1.20E+00	1.66
Demanufacturing	3.43E-01	0.451	2.84E-01	0.394	3.47E-01	0.547	2.90E-01	0.400
Cu smelting	5.15E-01	0.675	4.32E-01	0.600	N/A	N/A	4.38E-01	0.606
Unregulated	3.40E-01	0.446	2.81E-01	0.390	3.43E-01	0.541	2.87E-01	0.396
Total	**8.11E+00**	**10.6**	**6.71E+00**	**9.31**	**7.98E+00**	**12.6**	**6.84E+00**	**9.45**
GRAND TOTAL	**7.62E+01**	**100**	**7.20E+01**	**100**	**6.34E+01**	**100**	**7.23E+01**	**100**

*The impact scores are in units of kilograms cancertox-equivalents/1,000 cc of solder paste applied to a printed wiring board.
N/A=not applicable

Upstream occupational cancer impacts arise from the inputs to the extraction and processing of the various metals present in the alloys. When evaluating the upstream impacts alone, the tin production process group is the greatest contributor for all alloys, responsible for about 7 to 12 percent of total impacts. For SAC and SABC, silver production is the second greatest upstream contributor (1.3 and 0.82 percent, respectively). For BSA, bismuth production is the second greatest contributor at 0.87 percent, followed by silver production at 0.44 percent.

Top Contributors to Occupational Impacts (Paste Solder)

Table 3-77 presents the specific materials or flows contributing at least 1 percent of occupational *non-cancer* impacts by solder. The top contributors are driven by inputs in the use/application stage, manufacturing stage, and EOL stage. Solder paste inputs to reflow application are the top contributors for each solder paste, accounting for 31 to 33 percent of total impacts, depending on the alloy. The next greatest contributors are primary lead or silver used in paste manufacturing (25 to 26 percent), and solder on PWBs going to landfilling (22 to 23 percent). Secondary (i.e., recycled) alloys used in solder manufacturing contribute between 4 and 11 percent to total occupational non-cancer impacts. Smaller contributors to total occupational non-cancer impacts are solder on PWBs going to incineration (contributing about 6 percent), copper smelting (1 percent), unregulated recycling/disposal (1 percent), and demanufacturing (1 percent).

To better understand how the impact scores are derived and why lead-based impacts are far greater than other impacts in this impact category, an example from the solder manufacturing process is presented here. The quantity of primary and secondary lead in the input inventory for SnPb solder manufacturing is 2.3 kg per functional unit. This quantity is then multiplied by a toxicity HV to provide a toxicity equivalency for each potentially toxic chemical. For lead, the non-cancer HV is high (e.g., about 62,400, which is a unitless, relative value based on the quotient of the mean inhalation NOAEL for 84 chemicals of 69 mg/m^3 and a lead inhalation NOAEL value of 0.0011 mg/m^3). Lead's high HV gives it a very high relative toxicity compared to other toxic materials, which causes the occupational non-cancer impacts from lead to be far greater than those from other chemicals in the input inventory, especially when combined with lead's relatively high input amount. In addition, this high score for lead causes the SnPb alloy impacts to be far greater than those from the other alloys that do not contain lead.

For the lead-free alloys, silver has the highest non-cancer toxicity of the constituent metals, although the toxicity is not as great as that of lead. For example, in solder manufacturing the inventory input quantities of silver for the three lead-free alloys range from 0.061 to 0.21 kg/functional unit, and the silver non-cancer HV is 10,000 (unitless), based on an oral LOAEL. Although the relative toxicity is less than that of lead, the silver toxicity (indicated by the HV) is large and causes the manufacturing impacts for the lead-free solders to be driven by silver. This is true even though, compared to the other metals, the relative quantity of silver in the alloys is small and the actual inventory amount is small. Similarly, silver-bearing alloys at the EOL contribute significantly to the total impacts for the lead-free alloys. Again, this is because the HVs for the alloys are a weighted average of the HVs of the constituent metals, and the non-cancer HV for silver is 10,000 (unitless), compared to those of tin, copper, and bismuth, which are 1, 26, and 0.0043, respectively.

Table 3-77. Top contributors to occupational non-cancer impacts (paste solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	Use/application	SnPb (paste) reflow application	Sn-Pb solder paste	31.2
	Manufacturing	SnPb paste manufacturing	Lead (99.995%)	24.5
	End-of-life	Solder landfilling (SnPb)	Sn-Pb solder on PWB to landfill	22.4
	Manufacturing	SnPb paste manufacturing	Sn-Pb alloy secondary	10.6
	End-of-life	Solder incineration (SnPb)	Sn-Pb solder on PWB to incineration	5.92
	End-of-life	Post-consumer copper smelting (SnPb)	Sn-Pb solder on shredded PWB	1.40
	End-of-life	Demanufacturing- SnPb	Sn-Pb solder on PWB to recycling	1.40
	End-of-life	Unregulated recycling and disposal (SnPb)	Sn-Pb solder to unregulated recycling	1.40
	Manufacturing	Sn-Pb paste manufacturing	Lead secondary	1.18
SAC	Use/application	SAC (paste) reflow application	SAC solder paste	31.5
	Manufacturing	SAC paste manufacturing	Silver	25.3
	End-of-life	Solder landfilling (SAC)	SAC solder on PWB to landfill	22.7
	Manufacturing	SAC paste manufacturing	SAC alloy secondary	9.49
	End-of-life	Solder incineration (SnAgCu)	SAC solder on PWB to incineration	5.99
	End-of-life	Unregulated recycling and disposal (SAC)	SAC solder to unregulated recycling	1.42
	End-of-life	Demanufacturing-SAC	SAC solder on PWB to recycling	1.42
	End-of-life	Post-consumer copper smelting (SAC)	SAC solder on shredded PWB	1.42
BSA	Use/application	BSA (paste) reflow application	BSA solder paste	32.5
	Manufacturing	BSA paste manufacturing	Silver	25.8
	End-of-life	Solder landfilling (BSA)	BSA solder on PWB to landfill	23.4
	End-of-life	Solder incineration (BSA)	BSA solder on PWB to incineration	6.17
	Manufacturing	BSA paste manufacturing	BSA alloy secondary	4.43
	End-of-life	Unregulated recycling and disposal (BSA)	BSA solder to unregulated recycling	1.46
	End-of-life	Demfg-BSA	BSA solder on PWB to recycling	1.46
SABC	Use/application	SABC (paste) reflow application	SABC solder paste	31.5
	Manufacturing	SABC paste manufacturing	Silver	25.1
	End-of-life	Solder landfilling (SABC)	SABC solder on PWB to landfill	22.6
	Manufacturing	SABC paste manufacturing	SABC alloy secondary	9.39
	End-of-life	Solder incineration (SABC)	SABC solder on PWB to incineration	5.96
	End-of-life	Post-consumer copper smelting (SABC)	SABC solder on shredded PWB	1.41
	End-of-life	Unregulated recycling and disposal (SABC)	SABC solder to unregulated recycling	1.41
	End-of-life	Demanufacturing-SABC	SABC solder on PWB to recycling	1.41

Table 3-78 presents the specific materials or flows contributing at least 1 percent of occupational *cancer* impacts by solder. Natural gas from electricity generation needed for reflow application is the greatest contributor to occupational cancer impacts for all solder paste alloys, ranging from 38 to 43 percent contribution of total impacts depending on the solder. The high impact score for natural gas is primarily due to the large amount of natural gas inputs to the electricity generation process. No cancer WOE classification or slope factor was available for natural gas. Consequently, it was assigned a default cancer HV of 1, representative of a mean HV. The remaining top contributors shown in Table 3-78 include several different flows, all of which contribute approximately 13 percent or less. These include solder paste used in reflow application processes, natural gas used in tin production, tin used in solder paste manufacturing, lead used in solder paste manufacturing, and solder on PWBs going to landfills. One particular input, "casting process additive," is labeled as such to protect the confidentiality of the material. Flux materials used in production of the paste constitute greater than 1 percent of total occupational cancer impacts when they are taken together as a whole. None of the individual flux components, however, account for at least 1 percent of the total impacts and, as such, are not presented in the table.

Table 3-78. Top contributors to occupational cancer impacts (paste solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	Use/application	Electricity generation for (paste) reflow application	Natural gas (resource)	43.2
	Use/application	SnPb (paste) reflow application	SnPb solder paste	10.9
	Upstream	Tin production	Natural gas (resource)	7.60
	End-of-life	Solder landfilling (SnPb)	SnPb solder on PWB to landfill	7.12
	Manufacturing	SnPb paste manufacturing	Casting process additive	4.95
	Manufacturing	SnPb paste manufacturing	Tin	4.89
	Manufacturing	Post-industrial SnPb recycling	Dross	4.64
	Manufacturing	SnPb paste manufacturing	SnPb alloy secondary	3.36
	Manufacturing	SnPb paste manufacturing	Lead (99.995%)	2.87
	End-of-life	Solder incineration (SnPb)	SnPb solder on PWB to incineration	1.88
	Manufacturing	Natural gas production for paste manufacturing	Natural gas (resource)	1.47
	Manufacturing	SnPb paste manufacturing	Natural gas free customer USA	1.41
	Manufacturing	SnPb paste manufacturing	LFSP fluxes *	1.22
SAC	Use/application	Electricity generation	Natural gas (resource)	43.0
	Upstream	Tin production-DEAM	Natural gas (resource)	11.8
	Use/application	SAC (paste) reflow application	SAC solder paste	9.71
	Manufacturing	SAC paste manufacturing	Tin	7.58
	End-of-life	Solder landfilling (SAC)	SAC solder on PWB to landfill	6.23
	Manufacturing	SAC paste manufacturing	Casting process additive	4.58
	Manufacturing	Post-industrial SAC recycling	Dross	3.77
	Manufacturing	SAC paste manufacturing	SAC alloy secondary	2.61
	End-of-life	Solder incineration (SAC)	SAC solder on PWB to	1.64

Table 3-78. Top contributors to occupational cancer impacts (paste solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
			incineration	
	Manufacturing	Post-industrial SAC recycling	Heavy fuel oil	1.45
	Manufacturing	Natural gas production for solder manufacturing	Natural gas (resource)	1.29
	Upstream	Silver production	Natural gas (resource)	1.28
	Manufacturing	SAC paste manufacturing	Natural gas free customer USA	1.24
	Manufacturing	SAC paste manufacturing	LFSP fluxes *	1.13
BSA	Use/application	Electricity generation for (paste) reflow application	Natural gas (resource)	37.9
	Use/application	BSA (paste) reflow application	BSA solder paste	13.2
	End-of-life	Solder landfilling (BSA)	BSA solder on PWB to landfill	8.58
	Manufacturing	BSA paste manufacturing	Bismuth (co-mined from Pb, Cu)	7.88
	Upstream	Tin production	Natural gas (resource)	6.80
	Manufacturing	BSA paste manufacturing	Casting process additive	6.02
	Manufacturing	BSA paste manufacturing	Tin	4.38
	End-of-life	Solder incineration (BSA)	BSA solder on PWB to incineration	2.27
	Manufacturing	Post-industrial BSA recycling	Dross	2.27
	Manufacturing	BSA paste manufacturing	BSA alloy secondary	1.63
	Manufacturing	BSA paste manufacturing	LFSP fluxes *	1.48
	Manufacturing	Natural gas production for solder manufacturing	Natural gas (resource)	1.30
	Manufacturing	BSA paste manufacturing	Natural gas free customer USA	1.24
SABC	Use/application	Electricity generation	Natural gas (resource)	42.9
	Upstream	Tin production	Natural gas (resource)	11.8
	Use/application	SABC (paste) reflow application	SABC solder paste	9.85
	Manufacturing	SABC paste manufacturing	Tin	7.61
	End-of-Life	Solder landfilling (SABC)	SABC solder on PWB to landfill	6.33
	Manufacturing	SABC paste manufacturing	Casting process additive	4.58
	End-of-Life	Post-industrial SABC recycling	Dross	3.74
	Manufacturing	SABC paste manufacturing	SABC alloy secondary	2.63
	End-of-Life	Solder incineration (SABC)	SABC solder on PWB to incineration	1.67
	End-of-Life	Post-industrial SABC recycling	Heavy fuel oil	1.44
	Manufacturing	Natural gas production for solder manufacturing	Natural gas (resource)	1.29
	Manufacturing	SABC paste manufacturing	Natural gas free customer USA	1.24
	Manufacturing	SABC paste manufacturing	LFSP fluxes *	1.13

* The fluxes have been combined together to represent one flow. Taken individually, the fluxes do not contribute at least 1 percent of the total occupational cancer impact score.

Of note is that none of the top material contributors to the occupational cancer impacts are known or suspected human carcinogens with slope factors that would give a hazard value other than one or zero. They either have a cancer WOE classification that results in a cancer HV of either zero or one, or they lack data and are given a cancer HV of one. For example, based on their respective WOE designations, lead has a cancer HV equal to one and silver has a cancer HV equal to zero. The solder paste and solders on the PWBs at EOL have cancer HVs slightly below one because they are the weighted average of the individual metals' HVs that are a combination of one and zero values. This indicates that all the top contributors to this impact category are used in large enough quantities in the inventory to make them top contributors, but their carcinogenicity is largely unknown. The occupational cancer impacts, therefore, represent a lack of data rather than known carcinogenic hazards.

3.2.11.3 Bar solder results

Total Occupational Impacts by Life-Cycle Stage (Bar Solder)

Table 3-79 presents the bar solder results for occupational *non-cancer* impacts by life-cycle stage, based on the impact assessment methodology presented above. The table below lists the occupational non-cancer impact scores per functional unit for the life-cycle stages of each bar solder alloy, as well as the percent contribution of each life-cycle stage to the total impacts. Figure 3-27 shows the results in a stacked bar chart.

Table 3-79. Occupational non-cancer impacts by life-cycle stage (bar solder)

Life-cycle stage	**SnPb**		**SAC**		**SnCu**	
	Score*	%	Score*	%	Score*	%
Upstream	5.84E+00	0.0008	1.36E+01	0.125	9.23E+00	14.1
Manufacturing	2.22E+05	31.1	3.53E+03	32.5	2.07E+01	31.7
Use/application	2.13E+05	29.9	3.17E+03	29.2	2.25E+01	34.5
End-of-life	2.79E+05	39.1	4.14E+03	38.1	1.28E+01	19.7
Total	**7.15E+05**	**100**	**1.09E+04**	**100**	**6.53E+01**	**100**

*The impact scores are in units of kg noncancertox-equivalents/1,000 cubic centimeters of solder applied to a printed wiring board.

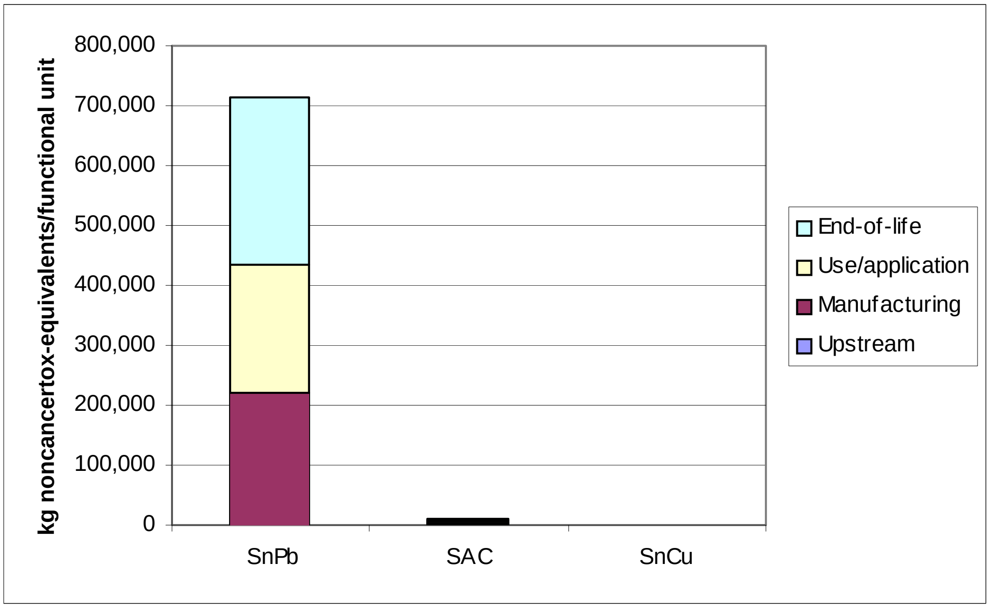


Figure 3-27. Bar Solder Total Life-Cycle Impacts: Occupational Non-Cancer

As described with the paste solder results, occupational impact scores are based on the potential toxicity of material *inputs* to each process. As mentioned above, this characterization method does not necessarily indicate where actual exposure is occurring; instead, it uses the inputs of potentially toxic materials as surrogates for potential exposure.

As shown in the figure, the occupational non-cancer impact score for SnPb (715,000 kg noncancertox-equivalents/functional unit) is far greater than the scores for the other solder alloys (10,900 and 65.3 kg noncancertox-equivalents/functional unit). Because SnPb has a higher inherent toxicity compared to the other alloys (based on the toxicity of the constituent metals), its potential impacts are larger.

Three life-cycle stages largely contribute to total impacts, regardless of the solder type: manufacturing, use/application, and EOL. The EOL stage was the largest contributor for SnPb (39 percent) and SAC (38 percent), followed by the manufacturing stage (31 and 33 percent), and the use/application stage (30 and 29 percent). Upstream impacts for SnPb and SAC are nominal (0.0008 and 0.125 percent). For SnCu, the same three life-cycle stages dominate, however, the use/application stage is the top contributor at nearly 35 percent, followed by the manufacturing stage (32 percent), and the EOL stage (20 percent). The upstream impacts are a larger percent (14 percent) of the total impacts for SnCu than it is for the other alloys. SnCu is different from SnPb and SAC since it does not contain the highly toxic lead or silver, thus, the overall distribution of impacts among life-cycle stages is different. SnCu is more driven by the quantity of materials with more modest toxicities rather than very high toxicities of a few materials.

Table 3-80 presents the bar solder results for occupational human health *cancer* impacts by life-cycle stage, based on the impact assessment methodology presented above. The table lists the occupational cancer impact scores per functional unit for the life-cycle stages of each bar solder, as well as the percent contribution of each life-cycle stage to the total impacts. Figure 3-28 presents the results in a stacked bar chart.

Table 3-80. Occupational cancer impacts by life-cycle stage (bar solder)

Life-cycle stage	SnPb		SAC		SnCu	
	Score*	%	Score*	%	Score*	%
Upstream	5.84E+00	9.83	1.33E+01	23.2	9.23E+00	16.8
Manufacturing	1.89E+01	31.8	1.30E+01	22.6	1.39E+01	25.4
Use/application	2.23E+01	37.6	2.09E+01	36.3	2.11E+01	38.4
End-of-life	1.23E+01	20.8	1.03E+01	17.9	1.06E+01	19.4
Total	**5.94E+01**	**100**	**5.75E+01**	**100**	**5.49E+01**	**100**

*The impact scores are in units of kg cancertox-equivalents/1,000 cubic centimeters of solder applied to a printed wiring board.

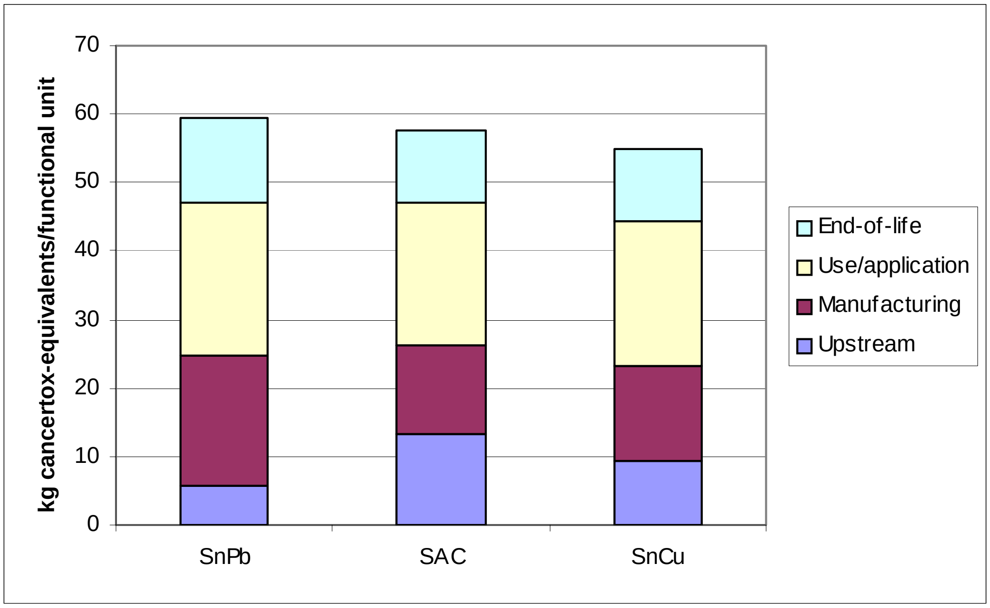


Figure 3-28. Bar Solder Total Life-Cycle Impacts: Occupational Cancer

As shown in the preceding table and figure, SnPb has the greatest occupational cancer impact score (59.4 kg cancertox-equivalents/functional unit), but its score is not significantly higher than those for SAC and SnCu (57.5 and 54.9 kg cancertox-equivalents/functional unit, respectively). In fact, the results for these three alloys may be indistinguishable given the uncertainties in the data.

Similar to the paste results, the bar solder occupational cancer scores are impacted largely by each of the four life-cycle stages. For all three bar solders, the use/application stage is the greatest contributor to total occupational cancer impacts, ranging from 36 to 38 percent. Potential impacts from the manufacturing stage range from 23 to 32 percent, while EOL stage impacts range from 18 to 21 percent depending on the alloy. Contributions from the upstream life-cycle stage range from 10 to 23 percent.

As discussed in the paste results for occupational cancer toxicity, very few chemicals in the inventory are known carcinogens or have some quantitative measure of carcinogenicity. The lack of carcinogenicity data is one of the major limitations and uncertainties in the occupational cancer characterization method and is addressed further in Section 3.2.11.4 (Limitations and Uncertainties).

Occupational Impacts by Process Group (Bar Solder)

Table 3-81 lists the occupational *non-cancer* impacts of each of the process groups in the life-cycle of the bar solders. As noted above for non-cancer impacts, the manufacturing, use/application, and EOL stages all largely contribute to occupational non-cancer impacts for all of the solder alloys. Within the manufacturing stage, the impacts from solder manufacturing are greater than post-industrial recycling, accounting for 18 to 33 percent of total impacts for all alloys, compared to less than 0.2 percent for post-industrial recycling. This is because the major contributors to the manufacturing impacts are the metals inputs used in production of the alloys (discussed below in the "*Top Contributors*" section), and the non-cancer hazard values of some of those metals (e.g., lead and silver) are very high. On the other hand, the inputs to the post-industrial recycling processes (e.g., dross inputs, which are outputs from the solder manufacturing process) do not have associated toxicity data to develop a hazard value, so the default hazard value is used, which is far below that of lead and silver. Solder manufacturing is the greatest contributor to occupational non-cancer impacts because it has the greatest quantity of solder inputs, and because occupational impacts are based on the quantity and potential toxicity of those inputs.

The wave application process group within the use/application stage is comprised of the wave soldering process and associated electricity generation. Use/application impacts for occupational non-cancer, therefore, are from the inputs to the wave solder process itself, as well as inputs to the electricity generation process.

Landfilling is the greatest contributor to EOL occupational non-cancer impacts (10 to 20 percent of total impacts) for all of the alloys, followed by unregulated recycling/disposal (6 to 12 percent of total impacts. Incineration contributes between 2 and 5 percent of total impacts, while demanufacturing and copper smelting each contribute approximately 1 percent or less to the total occupational non-cancer impacts for all bar solder alloys.

Like the solder manufacturing process group discussed above, landfilling and incineration dominate occupational non-cancer health impacts at EOL because these dispositions have the greatest inputs of EOL solder, the toxicity and overall quantity of which contribute to the determination of the overall impact score. Furthermore, the LCIA methodology uses input quantities as surrogates for exposure, in lieu of incorporating an exposure model as would be done in a chemical risk assessment. For example, within an alloy life-cycle, at this time most electronics are destined for landfilling (at least 72 percent) as modeled in the LFSP and, as a result, the LCIA methodology assumes most occupational exposure to solders occurs during landfilling. The landfilling impacts dominate EOL within each alloy life-cycle. This occurs despite the fact that there may actually be less true occupational exposure to a landfill worker than to a demanufacuturer or copper smelter worker. Given the screening nature of the LCIA occupational impact category method, the process with the greatest quantities of potentially toxic materials would tend to have the greatest impacts for a given set of similar materials. For this reason, the scores for demanufacturing and unregulated recycling/disposal are identical because the LFSP model assumes that equal amounts of EOL solder go to both of those dispositions. No mass is assumed to be lost between demanufacturing inputs and copper smelting inputs. The occupational non-cancer impacts from demanufacturing and copper smelting are the same because they have the same mass of solder inputs. They are not the same for SnCu because other inputs from fuel production processes affect the scores, which are not overshadowed by lead or silver toxicity as is the case with SnPb and SAC.

Table 3-81. Occupational non-cancer impacts by life-cycle stage and process group (bar solder)

Life-cycle stage	**SnPb**		**SAC**		**SnCu**	
Process group	Score*	%	Score*	%	Score*	%
UPSTREAM						
Sn production	5.64E+00	0.0008	1.19E+01	0.110	9.22E+00	14.1
Pb production	2.01E-01	0.00003	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	1.62E+00	0.0149	N/A	N/A
Cu production	N/A	N/A	6.35E-03	0.0001	6.23E-03	0.0095
Total	**5.84E+00**	**0.0008**	**1.36E+01**	**0.125**	**9.23E+00**	**14.1**
MANUFACTURING						
Solder manufacturing	2.22E+05	31.1	3.52E+03	32.5	1.16E+01	17.7
Post-industrial recycling	1.80E+01	0.0025	5.32E+00	0.0490	9.12E+00	14.0
Total	**2.22E+05**	**31.1**	**3.53E+03**	**32.5**	**2.07E+01**	**31.7**
USE/APPLICATION						
Solder application	2.13E+05	29.9	3.17E+03	29.2	2.25E+01	34.5
Total	**2.13E+05**	**29.9**	**3.17E+03**	**29.2**	**2.25E+01**	**34.5**
END-OF-LIFE						
Landfill	1.40E+05	19.5	2.07E+03	19.1	6.36E+00	9.74
Incineration	3.49E+04	4.88	5.17E+02	4.77	1.57E+00	2.41
Demanufacture	8.73E+03	1.22	1.29E+02	1.19	3.99E-01	0.611
Cu smelting	8.73E+03	1.22	1.29E+02	1.19	5.64E-01	0.865
Unregulated	8.73E+04	12.2	1.29E+03	11.9	3.95E+00	6.06
Total	**2.79E+05**	**39.1**	**4.14E+03**	**38.1**	**1.28E+01**	**19.7**
GRAND TOTAL	**7.15E+05**	**100**	**1.09E+04**	**100**	**6.53E+01**	**100**

*The impact scores are in units of kg noncancertox-equivalents/1,000 cc of solder applied to a printed wiring board.
N/A=not applicable

When evaluating the bar solder alloys against one another, SnPb has the greatest potential impacts versus the other alloys because the toxicity of lead is greater than the toxicity of the materials in the other alloys. These potential impacts are based only on the inherent toxicity of the materials and not their actual fate, transport, and final exposure.

Upstream occupational non-cancer impacts arise from the inputs to the extraction and processing of the various metals present in the alloys. Particularly for SnPb and SAC, the upstream impacts are very small compared to the total life-cycle impacts. Unlike SnPb and SAC, SnCu does not have toxic metals in its alloy composition (i.e., lead or silver), therefore, the impacts across the life-cycle are more evenly spread. Nonetheless, when evaluating the upstream impacts alone, tin production is the greatest contributor to the upstream impacts for all alloys. For SAC, the silver production process group is the second greatest upstream contributor (0.015 percent of total impacts).

Table 3-82 lists the occupational *cancer* impacts of each of the processes in the life-cycle of the solders. The use/application stage is the greatest contributor to occupational cancer impacts for the solders. The wave soldering process is the only process group within this stage; the only inputs modeled in the wave solder process are bar solder, flux, and electricity. Cancer impacts from the use/application stage, therefore, are based on the carcinogenic potential of the bar solder, flux, and any potentially carcinogenic inputs to the electricity generation process. When comparing alloys, the impacts from the use/application stage alone are all very close in magnitude with SnPb at 22.3 kg cancertox-equivalents/functional unit, followed closely by SnCu at 21.1 kg cancertox-equivalents/functional unit, and SAC at 20.9 kg cancertox-equivalents/functional unit.

Within the manufacturing stage, which is the second greatest contributor to occupational cancer impacts, the solder manufacturing process group impacts are greater than the post-industrial process group impacts for each solder. The solder manufacturing process group accounts for 18 to 19 percent and post-industrial recycling accounts for 4 to 13 percent of total impacts for all alloys.

Within the EOL stage, landfilling is the greatest contributor (about 9 to 10 percent of total impacts), followed by unregulated recycling/disposal (about 6 percent), and incineration (about 2 to 3 percent of total impacts). Demanufacturing and copper smelting are smaller contributors to the total occupational cancer impacts for all alloys (each less than 1 percent). Similar to the occupational non-cancer impacts discussed above, landfilling and incineration dominate impacts for this category because, instead of an exposure model, the impacts are based on the quantity of inputs to each process that have the potential to be toxic (carcinogenic, in this case). For example, within an alloy life-cycle, most electronics are destined for landfilling (at least 72 percent), as modeled in the LFSP, indicating that landfills have the greatest inputs of solder paste at EOL and, therefore, have the greatest EOL occupational cancer impacts. This is true despite the fact that there may actually be less occupational exposure to a landfill worker than to a demanufacuturer or copper smelter worker. Given the screening nature of the LCIA occupational impact category method, the process with the greatest quantities of potentially toxic materials would tend to have the greatest impacts for a given set of similar materials.

Table 3-82. Occupational cancer impacts by life-cycle stage and process group (bar solder)

Life-cycle stage	**SnPb**		**SAC**		**SnCu**	
Process group	Score*	%	Score*	%	Score*	%
UPSTREAM						

Table 3-82. Occupational cancer impacts by life-cycle stage and process group (bar solder)

Life-cycle stage	**SnPb**		**SAC**		**SnCu**	
Process group	Score*	%	Score*	%	Score*	%
Sn production	5.64E+00	9.51	1.19E+01	20.8	9.22E+00	16.8
Pb production	1.93E-01	0.325	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	1.37E+00	2.38	N/A	N/A
Cu production	N/A	N/A	6.29E-03	0.0109	6.17E-03	0.0112
Total	**5.84E+00**	**9.83**	**1.33E+01**	**23.2**	**9.23E+00**	**16.8**
MANUFACTURING						
Solder manufacturing	1.11E+01	18.6	1.05E+01	18.3	9.64E+00	17.6
Post-industrial recycling	7.85E+00	13.2	2.51E+00	4.37	4.31E+00	7.85
Total	**1.89E+01**	**31.8**	**1.30E+01**	**22.6**	**1.39E+01**	**25.4**
USE/APPLICATION						
Solder application	2.23E+01	37.6	2.09E+01	36.3	2.11E+01	38.4
Total	**2.23E+01**	**37.6**	**2.09E+01**	**36.3**	**2.11E+01**	**38.4**
END-OF-LIFE						
Landfill	6.09E+00	10.3	5.09E+00	8.85	5.25E+00	9.56
Incineration	1.50E+00	2.53	1.26E+00	2.18	1.30E+00	2.36
Demanufacture	3.82E-01	0.643	3.19E-01	0.555	3.29E-01	0.600
Cu smelting	5.72E-01	0.963	4.85E-01	0.844	4.94E-01	0.901
Unregulated	3.78E+00	6.37	3.16E+00	5.49	3.26E+00	5.94
Total	**1.23E+01**	**20.8**	**1.03E+01**	**17.9**	**1.06E+01**	**19.4**
GRAND TOTAL	**5.94E+01**	**100**	**5.75E+01**	**100**	**5.49E+01**	**100**

*The impact scores are in units of kg cancertox-equivalents/1,000 cubic centimeter of solder applied to a printed wiring board.
N/A=not applicable

Upstream occupational cancer impacts arise from the inputs to the extraction and processing of the various metals present in the alloys. When evaluating the upstream impacts alone, tin production is the greatest contributor for all alloys, responsible for about 10 to 21 percent of total impacts. For SAC, silver production is the second greatest upstream contributor (2.4 percent).

Top Contributors to Occupational Impacts (Bar Solder)

Table 3-83 presents the specific materials or flows contributing at least 1 percent of occupational *non-cancer* impacts by solder. The top contributors are driven by inputs in the use/application stage, manufacturing stage, and EOL stage for all three alloys, as well as the upstream stage for SnCu. Bar solder inputs to the wave application process are the top contributors for each bar solder alloy, accounting for approximately 15 to 30 percent of total impacts, depending on the alloy. There are several other top contributors depending on the alloy, including primary lead, silver, or copper used in paste manufacturing (9 to 28 percent), and solder on PWBs going to landfilling (10 to 20 percent). Solder sent to unregulated recycling/disposal contributes between 6 and 12 percent, and secondary (i.e., recycled) alloys used in solder manufacturing contribute between 4 and 14 percent to total occupational non-cancer impacts. SnCu does not have impacts from silver or lead; however, SnPb and SAC both have high relative toxicities. There are other materials that contribute greater than 1 percent to SnCu impacts that do not appear in the top contributors for SnPb and SAC. For example, flux materials contribute between 1 and 3 percent to total impacts for SnCu. As discussed in the paste solder results, the SnPb impacts are far greater than SAC and SnCu due to the high relative toxicity of lead.

Table 3-83. Top contributors to occupational non-cancer impacts (bar solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	Use/application	SnPb (bar) wave application	SnPb solder bar	29.8
	End-of-life	Solder landfilling (SnPb)	SnPb solder on PWB to landfill	19.5
	Manufacturing	SnPb bar manufacturing	Lead	17.1
	Manufacturing	SnPb bar manufacturing	SnPb alloy secondary	14.0
	End-of-life	Unregulated recycling and disposal (SnPb)	SnPb solder to unregulated recycling	12.2
	End-of-life	Solder incineration (SnPb)	SnPb solder on PWB to incineration	4.88
	End-of-life	Post-consumer copper smelting (SnPb)	SnPb solder on shredded PWB	1.22
	End-of-life	Demanufacturing-SnPb	SnPb solder on PWB to recycling	1.22
SAC	Use/application	SAC (bar) wave application	SAC solder bar	29.1
	Manufacturing	SAC bar manufacturing	Silver	28.1
	End-of-life	Solder landfilling (SAC)	SAC solder on PWB to landfill	19.1
	End-of-life	Unregulated recycling and disposal (SAC)	SAC Solder to unregulated recycling	11.9
	End-of-life	Solder incineration (SAC)	SAC solder on PWB to incineration	4.77
	Manufacturing	SAC bar manufacturing	SAC alloy secondary	4.30
	End-of-life	Post-consumer copper smelting (SAC)	SAC solder on shredded PWB	1.19
	End-of-life	Demanufacturing-SAC	SAC solder on PWB to recycling	1.19
SnCu	Use/application	SnCu (bar) wave application	SnCu solder bar	14.8
	Upstream	Tin production	Natural gas (resource)	14.1
	End-of-life	Solder landfilling (SnCu)	SnCu solder on PWB to landfill	9.66
	Manufacturing	SnCu bar manufacturing	Tin	9.06
	Use/application	Electricity generation	Natural gas (resource)	8.33
	End-of-life	Unregulated recycling and disposal (SnCu)	SnCu solder to unregulated recycling	6.04
	Manufacturing	Post-Industrial SnCu recycling	Fluorosilicic acid	5.14
	Manufacturing	Post-Industrial SnCu recycling	Dross	4.31
	Manufacturing	SnCu bar manufacturing	Sn-Cu alloy secondary	3.76
	Use/application	SnCu (bar) wave application	Flux C *	3.12
	Use/application	SnCu (bar) wave application	Flux D *	2.60
	Use/application	SnCu (bar) wave application	Flux F *	2.60
	End-of-life	Solder incineration (SnCu)	Sn-Cu solder on PWB to incineration	2.42

Table 3-83. Top contributors to occupational non-cancer impacts (bar solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
	Manufacturing	Post-Industrial SnCu recycling	Fluoroboric acid	2.25
	Manufacturing	SnCu bar manufacturing	Copper	2.09
	Manufacturing	Post-industrial SnCu recycling	Heavy fuel oil	1.66
	Use/application	SnCu (bar) wave application	Flux E *	1.56
	Use/application	SnCu (bar) wave application	Flux A *	1.04

* The chemical names of the fluxes have been withheld to protect confidentiality.

Table 3-84 presents the specific materials or flows contributing at least 1 percent of occupational *cancer* impacts by solder. The top contributors to the SnPb impacts are bar solder from wave application, solder on a PWB going to a landfill, and dross inputs to post-industrial recycling. For SAC and SnCu, the top contributors are natural gas from tin production, bar solder from wave application, and tin from bar manufacturing. As explained under the paste solder results, the high impact score for natural gas is primarily due to the relatively large amount of natural gas inputs to the associated processes. No cancer WOE classification or slope factor was available for natural gas. Consequently, it was assigned a default cancer HV of 1, representative of a mean HV. The remaining top contributors shown in Table 3-84 include several different flows, all of which contribute approximately 10 percent or less.

Table 3-84. Top contributors to occupational cancer impacts (bar solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	Use/application	SnPb (bar) wave application	SnPb solder bar	15.5
	End-of-life	Solder landfilling (SnPb)	SnPb solder on PWB to landfill	10.1
	Manufacturing	Post-industrial SnPb recycling	Dross	10.0
	Upstream	Tin production	Natural gas (resource)	9.47
	Use/application	Electricity generation	Natural gas (resource)	8.77
	Manufacturing	SnPb bar manufacturing	SnPb alloy secondary	7.26
	End-of-life	Unregulated recycling and disposal (SnPb)	SnPb solder to unregulated recycling	6.34
	Manufacturing	SnPb bar manufacturing	Tin	6.09
	Use/application	SnPb (bar) wave application	Flux C *	3.43
	Manufacturing	SnPb bar manufacturing	Lead	3.29
	Use/application	SnPb (bar) wave application	Flux D *	2.86
	Use/application	SnPb (bar) wave application	Flux F	2.86
	End-of-life	Solder incineration (SnPb)	SnPb solder on PWB to incineration	2.54
	Manufacturing	Post-industrial SnPb recycling	Heavy fuel oil	1.92
	Use/application	SnPb (bar) wave application	Flux E *	1.72
	Use/application	SnPb (bar) wave application	Flux A *	1.14
	Use/application	SnPb (bar) wave application	Flux B *	1.14
SAC	Upstream	Tin production	Natural gas (resource)	20.7
	Use/application	SAC (bar) wave application	SAC solder bar	13.4

Table 3-84. Top contributors to occupational cancer impacts (bar solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
	Manufacturing	SAC bar manufacturing	Tin	13.3
	Use/application	Electricity generation	Natural gas (resource)	9.16
	End-of-life	Solder landfilling (SAC)	SAC solder on PWB to landfill	8.76
	End-of-life	Unregulated recycling and disposal (SAC)	SAC Solder to unregulated recycling	5.47
	Use/application	SAC (bar) wave application	Flux C *	3.54
	Use/application	SAC (bar) wave application	Flux D *	2.96
	Use/application	SAC (bar) wave application	Flux F *	2.96
	Manufacturing	Post-industrial SAC recycling	Dross	2.85
	Upstream	Silver production	Natural gas (resource)	2.37
	End-of-life	Solder incineration (SAC)	SAC solder on PWB to incineration	2.19
	Manufacturing	SAC bar manufacturing	SAC alloy secondary	1.97
	Use/application	SAC (bar) wave application	Flux E *	1.77
	Use/application	SAC (bar) wave application	Flux A *	1.18
	Use/application	SAC (bar) wave application	Flux B *	1.18
	Manufacturing	Post-industrial SAC recycling	Heavy fuel oil	1.10
	Manufacturing	Natural gas production in solder manufacturing	Natural gas (resource)	1.06
	Manufacturing	SAC bar manufacturing	Natural gas products	1.02
SnCu	Upstream	Tin production	Natural gas (resource)	16.7
	Use/application	SnCu (bar) wave application	SnCu solder bar	14.5
	Manufacturing	SnCu bar manufacturing	Tin	10.8
	Use/application	Electricity generation	Natural gas (resource)	9.60
	End-of-life	Solder landfilling (SnCu)	SnCu solder on PWB to landfill	9.47
	End-of-life	Unregulated recycling and disposal (SnCu)	SnCu solder to unregulated recycling	5.92
	Manufacturing	Post-industrial SnCu recycling	Dross	5.12
	Use/application	SnCu (bar) wave application	Flux C *	3.71
	Manufacturing	SnCu bar manufacturing	Sn-Cu alloy secondary	3.68
	Use/application	SnCu (bar) wave application	Flux D *	3.09
	Use/application	SnCu (bar) wave application	Flux F *	3.09
	End-of-life	Solder incineration (SnCu)	Sn-Cu solder on PWB to incineration	2.37
	Manufacturing	Post-industrial SnCu recycling	Crude oil products	2.18
	Manufacturing	Post-industrial SnCu recycling	Heavy fuel oil	1.97
	Manufacturing	Natural gas production for solder manufacturing	Natural gas (resource)	1.86
	Use/application	SnCu (bar) wave application	Flux E *	1.23
	Use/application	SnCu (bar) wave application	Flux A *	1.23
	Use/application	SnCu (bar) wave application	Flux B *	1.11
	Manufacturing	SnCu bar manufacturing	Natural gas products	1.06

* The chemical names of the fluxes have been withheld to protect confidentiality.

As discussed with the paste results, none of the top material contributors to the occupational cancer impacts are known or suspected human carcinogens with slope factors that would give a hazard value other than one or zero. They either have a cancer WOE classification that results in a cancer HV of either one or zero, or they lack data and are given a cancer HV of one. Thus, all the top contributors to this impact category are used in large enough quantities in the inventory to make them top contributors, but their carcinogenicity is largely unknown. The occupational cancer impacts, therefore, represent a lack of data rather than known carcinogenic hazards.

3.2.11.4 Limitations and uncertainties

Most of the limitations and uncertainties associated with the chronic human health results presented here and in Section 3.2.12 can be grouped into three categories:

1. *Structural or modeling limitations and uncertainties* associated with the accuracy of the toxic chemical classification method and the chemical scoring approach used to characterize human health effects.
2. *Toxicity data limitations and uncertainties* associated with the availability and accuracy of toxicity data to represent potential human health effects.
3. *LCI data limitations and uncertainties* associated with the accuracy and representativeness of the inventory data.

Each of these is discussed below:

Structural or modeling limitations and uncertainties. The chemical scoring method used in the human health effects impact characterization is a screening tool to identify chemicals of potential concern, not to predict actual effects or characterize risk. A major limitation in the method is that it only measures relative toxicity combined with inventory amount. It does not take chemical fate, transportation, or degradation into account. In addition, it uses a simple surrogate value (e.g., inventory amount) to evaluate the potential for exposure, when actual exposure potential involves many more factors, some of which are chemical-specific. The LCIA method for toxicity impacts also takes the most toxic endpoint to calculate a hazard value, regardless of the route of exposure (e.g., inhalation or ingestion); therefore, this approach does not model true potential exposures, but rather the relative toxicity as compared to other chemicals, to compare life-cycle results among alloys. This is addressed further in Section 3.2.12.4 with respect to public health impacts.

Other sources of uncertainty include possible omissions by the LFSP researchers in the impact classification process (e.g., potentially toxic chemicals not classified as such) or misrepresentation of chemicals in the impact characterization method itself (e.g., misrepresenting a chemical as a small contributor to total impacts, because of missing or inaccurate toxicity data). Some of these limitations and uncertainties also may be considered limits in the toxicity data which are discussed further below.

It should be noted, however, that because LCA involves analyzing many processes over the entire life-cycle of a product, a comprehensive, quantitative risk assessment of each chemical input or output cannot be done. Rather, LCA develops relative impacts that often lack temporal or spatial specificity, but can be used to identify materials for more detailed evaluation.

Toxicity data limitations and uncertainties. Major uncertainties in the impact assessment for potentially toxic chemicals result from missing toxicity data and from limitations of the available toxicity data. Uncertainties in the human health hazard data (as typically encountered in a hazard assessment) include the following:

- Using dose-response data from laboratory animals to represent potential effects in humans.
- Using data from homogenous populations of laboratory animals or healthy human populations to represent the potential effects on the general human populations with a wide range of sensitivities.
- Using dose-response data from high dose toxicity studies to represent potential effects that may occur at low levels.
- Using data from short-term studies to represent the potential effects of long-term exposures.
- Assuming a linear dose-response relationship.
- Possibly increased or decreased toxicity resulting from chemical interactions.

Uncertainty is associated with using a default HV (i.e., assuming average toxicity for that measure when a chemical could be either more or less toxic than average) for missing toxicity data; however, the use of neutral default values for missing data reduces the bias that typically favors chemicals with little available information. Use of a data-neutral default value to fill data gaps is consistent with principles for chemical ranking and scoring (Swanson and Socha, 1997). Of the 177 chemicals classified as potentially toxic in this LFSP LCA, 81 (46 percent) had no toxicity data for non-carcinogenic effects and 88 (50 percent) had no toxicity data for carcinogenic effects (e.g., WOE classification or slope factor). Sixty chemicals (34 percent) had no human health toxicity date whatsoever.

Specific to carcinogenic effects, the lack of measured carcinogenicity data is a major uncertainty in the occupational cancer results. The 88 potentially toxic chemicals with no carcinogenic toxicity data receive a median HV (HV=1), which is equal to the HV assigned to known or suspected carcinogens with no slope factor. Of the 89 chemicals that have cancer data, 30 received an HV of zero because they have WOE classifications of D or E or IARC classifications of 3 or 4 (i.e., not classifiable, non-carcinogenic, or probably not carcinogenic). Of the remaining 59 known or suspected carcinogens, 25 have the slope factors needed to calculate a hazard value other than 1, and none of the top material contributors to the occupational cancer impacts that are known or suspected human carcinogens have slope factors. The occupational cancer impacts, therefore, are largely distributed among the material inputs used in the greatest quantity in the solder life-cycle, but the relative carcinogenicity of these materials is uncertain.

For the solder alloys, either in paste or solid form, direct toxicity data are not available; however, instead of being given default HVs, they are given HVs based on the weighted average of the HVs of the constituent metals and fluxes (when applicable). Although the resulting HVs are not known to be completely representative of an appropriate HV for a solder, they are assumed to be the best estimates for this screening methodology given the available data. This introduces uncertainty only for the *occupational* impacts as the solders themselves are inputs to given processes and it is the inputs that are the basis for the impact characterization for occupational impacts. (Note that because the solders are given toxicity HVs does not mean that they are designated RCRA toxic wastes by the U.S. EPA; it only indicates that there is a potential for exposure to potentially toxic materials.) For the *public* health impacts, scores are based on outputs, which are the environmental releases of the individual metals when the solders break down and do not include the solders as a whole. The uncertainty in estimating an HV for an alloy using a weighted average of the constituent metals does not affect the public health impact categories. Instead, for the public health impacts which are based on outputs, there is uncertainty associated with predictions of how the metal constituents are partitioned and released to the environment, which is related to limitations in the inventory (discussed below).

<u>LCI data limitations and uncertainties</u>. For both paste and bar solders, the majority of non-cancer occupational impacts are spread out among three stages: manufacturing, EOL, and application stages. In most cases, the greatest impacts are from lead, silver, or secondary alloy inputs in manufacturing; solder used in application; and solder on PWBs at EOL. The quantities of these materials in the inventory represent surrogates for exposure. As a result, the potential relative toxicity of each alloy across their life-cycles is affected by (1) the amount of lead and silver inputs, which is closely related to the percent composition of those metals in the alloys; (2) the amount of paste or bar solder used in the application process, which is related to the volume of paste used, as determined with the functional unit definition; and, (3) the solder on a board at EOL, which is based on the functional unit definition. The lead and silver inputs from solder paste manufacturing data were collected as primary data for this project from three major manufacturers and averaged together. These data are considered to be of good quality as discussed in Chapter 2 and, therefore, the inventory uncertainty and limitations associated with the occupational non-cancer impacts from manufacturing are not anticipated to be too great. The impacts from application and EOL are based on the volume of solder applied to a board, which is the defined functional unit. This is based on the physical densities of the individual solders and is not expected to be a source of uncertainty in the inventory; however, there are EOL uncertainties related to the assumptions about EOL dispositions (e.g., 72 percent of solder goes directly to landfilling for SnPb, SAC, SABC, and SnCu) which determines the relative amount of solder in a functional unit assumed to be sent to each disposition. These are discussed in greater detail in Chapter 2, limitations and uncertainties in the EOL inventory.

The LCI data limitations for occupational cancer results also are similar to those for occupational non-cancer results; however, because the top contributing impacts in this impact category are from all life-cycle stages, the limitations and uncertainties are related to all life-cycle stages. In summary, the use/application limitations and uncertainties related to electricity inputs arise from the following: (1) for reflow soldering, reflow energy is based on a limited number of data points that cover a wide range, and (2) for reflow and wave soldering, electricity production data are from a secondary source. The reflow energy data are the subject of a sensitivity analysis in Section 3.3, but issues associated with electricity production data are not considered to be significant.

Uncertainties and limitations from the solder inputs in the use/application stage, the metal inputs in the solder manufacturing processes, and the solders on PWBs at EOL are related to the functional unit definition. Data on these solder inputs are from primary data collected for this project and are considered to be of good quality with no major limitations or uncertainties. EOL uncertainties, as mentioned above, are related to the assumptions about the percent of solder going to the various EOL dispositions. Limitations and uncertainties from the upstream life-cycle stage arise from the fact that the upstream metals production data are from secondary sources.

3.2.12 Public Human Health Impacts

This section presents the LCIA characterization methodology and the LCIA results for the public human health impact category. General information that is common to all the toxicity impact categories (i.e., occupational human health, public human health, and ecological toxicity) was presented in Section 3.2.11 and is applicable to this section. For chronic public health effects, the impact scores represent surrogates for potential health effects to residents living near a facility from long-term repeated exposure to toxic or carcinogenic agents. Impact scores are calculated for both cancer and non-cancer effects, and are based on the identity and amount of toxic chemical outputs with dispositions to air, soil and water.[1] As stated previously, inventory items do not truly represent long-term exposure, instead impacts are relative toxicity weightings of the inventory.

The scores for impacts to the public differ from occupational impacts in that inventory outputs are used as opposed to inventory inputs. This basic screening level scoring does not incorporate the fate and transport of the chemicals. The public human health impact results presented in this section include two impact categories: public non-cancer impacts and public cancer impacts.

3.2.12.1 Characterization

Section 3.2.11.1 (*Potential Human Health Impacts*) provides a general discussion of the human health characterization approach in this LCIA. Below are the specific equations used to calculate impact scores for potential public non-cancer and cancer impacts.

Public Human Health Characterization: Non-Cancer

The chronic public health effects impact score for non-cancer effects is calculated by:

$$(IS_{CHP\text{-}NC})_i = (HV_{NC} \times Amt_{TCoutput})_i$$

where:

$IS_{CHP\text{-}NC}$	equals the impact score for chronic non-cancer effects to the public for chemical *i* (kg non-cancertox-equivalent) per functional unit;
HV_{NC}	equals the hazard value for chronic non-cancer effects for chemical *i* (based on either inhalation or oral toxicity, see Section 3.2.11.1); and
$Amt_{TC\ output}$	equals the amount of toxic inventory output of chemical *i* to air, water, and soil (kg) per functional unit.

More detail on the HV_{NC} is provided in Section 3.2.11.1.

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[1] Disposition to soil includes direct, uncontained releases to soil as could occur from unregulated disposal. It does not include solid or hazardous waste disposal in a regulated landfill. Disposition to water, however, could include groundwater if a landfill model shows releases to groundwater, for example.

Public Human Health Characterization: Cancer

The chronic public health effects impact score for cancer effects is calculated as follows:

$$(IS_{CHP\text{-}CA})_i = (HV_{CA} \times Amt_{TCoutput})_i$$

where:

$IS_{CHP\text{-}CA}$	equals the impact score for chronic cancer health effects to the public for chemical *i* (kg cancertox-equivalent) per functional unit;
HV_{CA}	equals the hazard value for carcinogenicity for chemical *i* (based on either inhalation or oral carcinogenicity, see Section 3.2.11.1); and
$Amt_{TC\ output}$	equals the amount of toxic inventory output of chemical *i* to air, water, and soil (kg) per functional unit.

3.2.12.2 Paste solder results

Total Public Health Impacts by Life-Cycle Stage (Paste Solder)

Table 3-85 presents the solder paste results for public human health *non-cancer* impacts by life-cycle stage, based on the impact assessment methodology presented above. The table lists the public non-cancer impact scores per functional unit for the life-cycle stages of each paste solder alloy, as well as the percent contribution of each life-cycle stage to the total impacts. Figure 3-29 presents the results in a stacked bar chart.

Table 3-85. Public non-cancer impacts by life-cycle stage (paste solder)

Life-cycle stage	**SnPb**		**SAC**		**BSA**		**SABC**	
	Score*	%	Score*	%	Score*	%	Score*	%
Upstream	1.95E+02	0.222	7.80E+03	74.0	2.88E+03	57.4	5.10E+03	65.0
Manufacturing	4.74E+01	0.0538	3.50E+01	0.333	2.02E+01	0.404	3.51E+01	0.447
Use/application	2.86E+03	3.25	2.68E+03	25.5	2.10E+03	41.9	2.69E+03	34.3
End-of-life	8.49E+04	96.5	1.74E+01	0.165	1.62E+01	0.324	1.64E+01	0.209
Total	**8.80E+04**	**100**	**1.05E+04**	**100**	**5.01E+03**	**100**	**7.84E+03**	**100**

*The impact scores are in units of kilograms noncancertox-equivalents/1,000 cc of solder paste applied to a printed wiring board.

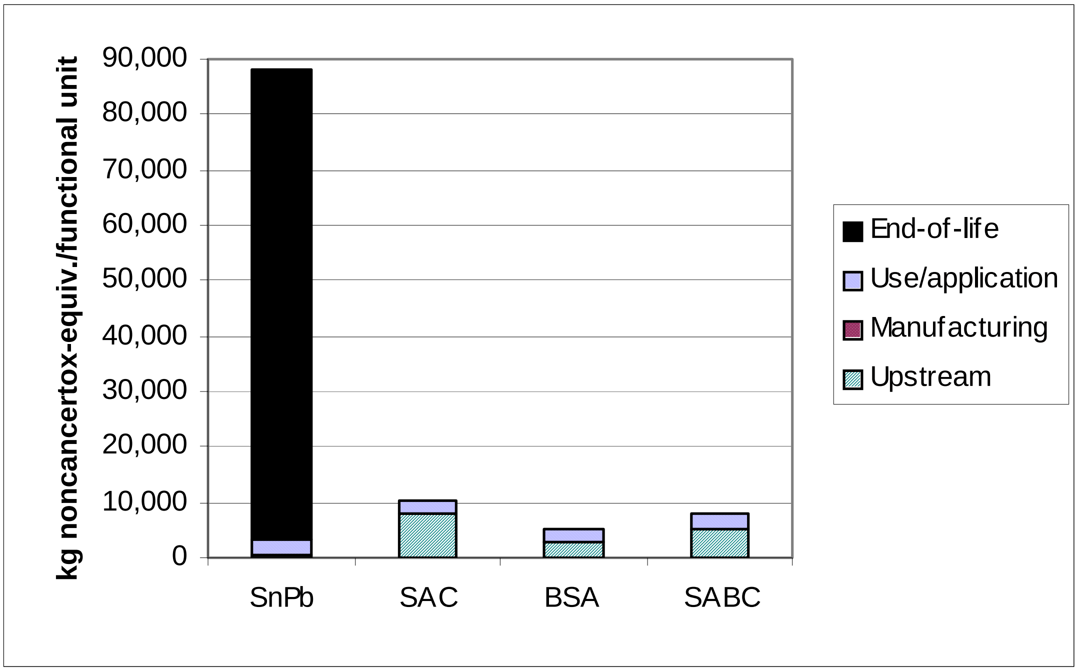

Figure 3-29. Solder Paste Total Life-Cycle Impacts: Public Non-Cancer

The public non-cancer impacts for SnPb (88,000 kg noncancertox-equivalents/functional unit) are far greater than the other alloys (ranging from 5,010 to 10,500 kg noncancertox-equivalents/functional unit for BSA and SAC, respectively). The EOL stage dominates impacts for SnPb, contributing nearly 97 percent to the total SnPb public non-cancer impacts. The EOL impacts for the other alloys contribute only about 0.2 to 0.3 percent of total impacts. EOL public non-cancer impacts are much greater for SnPb than the other solders due to lead's high HV combined with its greater leachability as determined by TCLP testing (see Chapter 2 and Appendix C), which is discussed further below.

For the lead-free alternatives, the upstream life-cycle stage is the greatest contributor to overall public non-cancer impacts. SAC has the greatest upstream public non-cancer impacts at 7,800 kg noncancertox-equivalents/functional unit, which is 74 percent of total SAC public non-cancer impacts. SABC has 5,100 kg noncancertox-equivalents/functional unit or 65 percent contribution to total SABC impacts. BSA has fewer upstream public non-cancer impacts with 2,880 kg noncancertox-equivalents/functional unit, a 57 percent contribution.

The use/application stage, which is made up of the reflow soldering process group, is the second greatest contributor for all alloys. Impacts from this life-cycle stage are associated with outputs from the generation of electricity used to power the reflow ovens and are greatest for the alloys that consume the most energy during use. For this stage, SnPb has the greatest impacts (2,860 kg noncancertox-equivalents/functional unit), followed by SABC, SAC, and BSA (2,690, 2,680, and 2,100 kg noncancertox-equivalents/functional unit, respectively). The percent contribution of the use/application stage to SnPb total impacts is relatively small (3 percent) compared to the lead-free alloys (about 26 to 42 percent for SAC and BSA, respectively). This is due to lead's high HV which causes its impact scores at EOL to be much greater than SnPb impact scores from solder reflow (e.g., from outputs from electricity generation). Life-cycle public non-cancer impacts from the manufacturing stage are relatively small for all of the solder paste alloys, ranging from 20.2 to 47.4 kg noncancertox-equivalents/functional unit or 0.05 to 0.4 percent of total impacts.

Table 3-86 presents the paste solder results for public human health *cancer* impacts by life-cycle stage, based on the impact assessment methodology presented above in Section 3.2.12.1. The table lists the public cancer impact scores per functional unit for the life-cycle stages of each solder paste alloy, as well as the percent contribution of each life-cycle stage to the total impacts. Figure 3-30 presents the results in a stacked bar chart.

Table 3-86. Public cancer impacts by life-cycle stage (paste solder)

Life-cycle stage	**SnPb**		**SAC**		**BSA**		**SABC**	
	Score*	%	Score*	%	Score*	%	Score*	%
Upstream	3.00E-01	4.31	2.01E+00	28.4	7.65E-01	14.9	1.43E+00	22.0
Manufacturing	1.16E-01	1.67	1.36E-01	1.93	6.09E-02	1.18	1.36E-01	2.08
Use/application	5.09E+00	73.2	4.80E+00	68.1	3.97E+00	77.0	4.82E+00	74.1
End-of-life	1.45E+00	20.8	1.10E-01	1.56	3.56E-01	6.92	1.20E-01	1.85
Total	**6.96E+00**	**100**	**7.05E+00**	**100**	**5.15E+00**	**100**	**6.51E+00**	**100**

*The impact scores are in units of kilograms cancertox-equivalents/1,000 cc of solder applied to a printed wiring board.

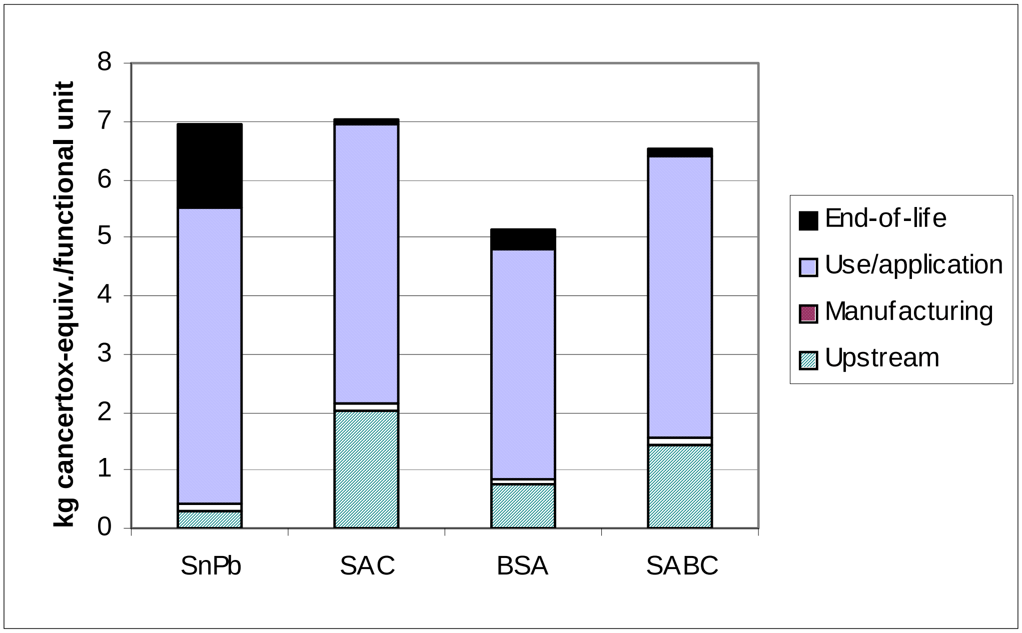

Figure 3-30. Solder Paste Total Life-Cycle Impacts: Public Cancer

The total public cancer impact scores for SAC and SnPb are very close at 7.05 and 6.96 kg cancertox-equivalents/functional unit, respectively, the distribution of their impacts across the solder life-cycle varies; that is, the use/application stage is the greatest contributor for both alloys. For SnPb, however, the EOL is the second greatest contributor by life-cycle stage, while, for SAC, the upstream life-cycle stage is the second greatest stage. The alloy with the next greatest public cancer impact score is SABC at 6.51 kg cancertox-equivalents/functional unit, while BSA has the lowest total score at 5.15 kg cancertox-equivalents/functional unit. The use/application stage dominates impacts for all solder alloys, ranging from 68 to 77 percent of total impacts.

While the EOL stage is the second greatest contributor to the SnPb total impact score at 21 percent of total impacts, it only contributes about 1.6 to 6.9 percent of the total scores of the lead-free alloys. For these alloys, the upstream life-cycle stage is the second greatest contributor, ranging from 15 to 28 percent. For SnPb, upstream processes contribute only about 4.3 percent of the total impacts. The manufacturing stage impacts are small for all the solder paste alloys, ranging from 1.7 to 2.0 percent, depending on the alloy.

To help put the public health impact scores into perspective, they are compared to impacts from burning a 60-watt lightbulb. The public health toxicity impacts associated with the electricity used to burn a 60-watt bulb for one day is 4,729 kg noncancertox-equivalents. The difference between the public health impacts for SnPb and SAC is 77,500 kg noncancertox-equivalents, which is equivalent to the public health impacts that would be associated with burning a 60-watt bulb for approximately 16 days straight.

For the cancer impacts, the small difference between SnPb and SAC (i.e., 0.09 kg cancertox-equivalents) is equivalent to the cancer impacts associated with burning a 60-watt lightbulb for approximately 18 minutes. The difference between the SnPb and SABC cancer scores (i.e., 1.18 kg cancertox-equivalents) is equivalent to running a 60-watt bulb continuously for 4 hours.

Public Health Impacts by Process Group (Paste Solder)

Table 3-87 lists the public *non-cancer* impacts of each of the process groups in the life-cycle of the solders. Within the EOL stage of the SnPb life-cycle, landfilling is the greatest contributor to total impacts (73 percent of total public non-cancer impacts), followed by incineration (19 percent), and unregulated recycling/disposal (4.5 percent). Copper smelting and demanufacturing are very small contributors to the total SnPb public non-cancer toxicity impacts (0.006 and 0.0003 percent, respectively).

EOL processes are much less significant to total public non-cancer impacts for the lead-free alloys. When evaluating these alloys alone, unregulated recycling and disposal is the greatest contributor to EOL impacts, with scores of 14.5, 14.8, and 13.1 kg noncancertox-equivalents/functional unit for SAC, BSA, and SABC, respectively. This process group only contributes approximately 0.1 to 0.3 percent to the total scores.

For the lead-free solders, the silver production process in the upstream life-cycle stage is the process group with the greatest contribution to public non-cancer impacts, accounting for 45 to 72 percent of total impacts. The next greatest contributor within the upstream life-cycle stage for SAC and SABC is tin production (1.9 and 2.5 percent contribution), while bismuth production is the next largest contributor for BSA at 10 percent, followed by tin production at 2 percent.

As noted previously, the second greatest contributor to lead-free solder public non-cancer impacts within all the life-cycle stages is the reflow solder application process, contributing 26 to 42 percent to the total public non-cancer impacts. The solder application process is the fourth largest contributor to SnPb public non-cancer impacts.

Table 3-87 also shows the contribution of the two process groups—solder manufacturing and post-industrial recycling—within the manufacturing stage which contribute a small proportion to the overall impacts for all of the solders. SnPb, SAC, and SABC have similar impact scores for solder manufacturing (20.5, 18.7, and 18.8 kg noncancertox-equivalents/functional unit, respectively), while the BSA score is lower (11.7 kg noncancertox-equivalents/functional unit). For the post-industrial recycling process group, impacts are greatest for SnPb (26.8 kg noncancertox-equivalents/functional unit), equal for SAC and SABC (16.3 kg noncancertox-equivalents/functional unit for both), and lowest for BSA (8.52 kg noncancertox-equivalents/functional unit). Total manufacturing impacts follow the same trend as the total life-cycle impacts with SnPb being greatest, SAC and SABC being approximately equal, and BSA being the lowest.

Table 3-87. Public non-cancer impacts by life-cycle stage and process group (paste solder)

Life-cycle stage	**SnPb**		**SAC**		**BSA**		**SABC**	
Process group	Score*	%	Score*	%	Score*	%	Score*	%
UPSTREAM								
Sn production	1.33E+02	0.151	1.95E+02	1.85	9.97E+01	1.99	1.97E+02	2.51
Pb production	6.18E+01	0.0703	N/A	N/A	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	7.60E+03	72.1	2.27E+03	45.3	4.89E+03	62.3
Cu production	N/A	N/A	5.47E+00	0.0519	N/A	N/A	4.58E+00	0.0583
Bi production	N/A	N/A	N/A	N/A	5.08E+02	10.1	7.68E+00	0.0979
Total	**1.95E+02**	**0.222**	**7.80E+03**	**74.0**	**2.88E+03**	**57.4**	**5.10E+03**	**65.0**
MANUFACTURING								
Solder manufacturing	2.05E+01	0.0233	1.87E+01	0.178	1.17E+01	0.234	1.88E+01	0.240
Post-industrial recycling	2.68E+01	0.0305	1.63E+01	0.155	8.52E+00	0.170	1.63E+01	0.208
Total	**4.74E+01**	**0.0538**	**3.50E+01**	**0.333**	**2.02E+01**	**0.404**	**3.51E+01**	**0.447**
USE/APPLICATION								
Reflow application	2.86E+03	3.25	2.68E+03	25.5	2.10E+03	41.9	2.69E+03	34.3
Total	**2.86E+03**	**3.25**	**2.68E+03**	**25.5**	**2.10E+03**	**41.9**	**2.69E+03**	**34.3**
END-OF-LIFE								

Table 3-87. Public non-cancer impacts by life-cycle stage and process group (paste solder)

Life-cycle stage	**SnPb**		**SAC**		**BSA**		**SABC**	
Process group	Score*	%	Score*	%	Score*	%	Score*	%
Landfill	6.39E+04	72.6	8.95E-01	0.0085	1.21E+00	0.0241	1.15E+00	0.0147
Incineration	1.71E+04	19.4	-6.30E-02	-0.0006	-7.30E-02	-0.0015	1.17E-01	0.0015
Demanufacture	2.81E-01	0.0003	2.43E-01	0.0023	2.86E-01	0.0057	2.44E-01	0.0031
Cu smelting	4.95E+00	0.0056	1.77E+00	0.0168	N/A	N/A	1.78E+00	0.0226
Unregulated	3.93E+03	4.47	1.45E+01	0.138	1.48E+01	0.295	1.31E+01	0.167
Total	**8.49E+04**	**96.5**	**1.74E+01**	**0.165**	**1.62E+01**	**0.324**	**1.64E+01**	**0.209**
GRAND TOTAL	**8.80E+04**	**100**	**1.05E+04**	**100**	**5.01E+03**	**100**	**7.84E+03**	**100**

*The impact scores are in units of kilograms noncancertox-equivalents/1,000 cc of solder paste applied to a printed wiring board.
N/A=not applicable

Table 3-88 lists the public *cancer* impacts of each of the process groups in the life-cycle of the solders. The impact scores from the use/application stage that dominate the scores for all alloys are predominately due to potentially carcinogenic outputs from electricity generation in the reflow application process group. Other contributing outputs are the flux materials released from the paste during solder reflow. EOL impacts arise from output flows of potentially carcinogenic materials released from the various EOL processes. Within the SnPb life-cycle, landfilling is the greatest process group contributor to EOL impacts (15 percent of total public cancer impacts), followed by incineration (4 percent), and unregulated recycling/disposal (2 percent). Copper smelting and demanufacturing are small contributors to the total SnPb public cancer impact scores (0.18 and 0.0061 percent, respectively). For SAC and SABC, unregulated disposal has the highest EOL impact score, albeit a small proportion of total impacts (1.3 and 1.4 percent, respectively). BSA has the most EOL impacts from landfilling, as well as unregulated recycling and disposal (both about 2.8 percent of the BSA total public cancer impact score), because it has a different EOL scenario than the other alloys (i.e., after demanufacturing, solder on boards is not sent to copper smelting, but instead either landfilled or incinerated). Other processes which contribute include incineration at 1.3 percent of the total impacts and demanufacturing at 0.01 percent.

Potential upstream impacts arise from outputs of potentially carcinogenic materials in the extraction and processing of the various metals present in the alloys. In the SnPb life-cycle, the public cancer impact scores from tin extraction and processing comprise about 3.8 percent of the total compared to about 0.53 percent for lead extraction and processing. For the lead-free alloys, silver production dominates upstream impacts, contributing about 9 to 23 percent of the total score depending on the alloy. Tin production, which is the second greatest contributor to upstream impacts for the lead-free alloys, accounts for about 4 to 6 percent of the total public cancer scores. Public cancer impacts from silver processing exceed impacts from tin processing in solders that contain both metals, even though the silver content of the alloys is much less than the tin content. For example, SAC is 95.5 percent tin and only 3.9 percent silver, yet its impacts from silver production are greater than those from tin production. This indicates that potential cancer impacts from silver extraction and processing outputs are disproportionately high compared to the other solder metals.

Table 3-88. Public cancer impacts by life-cycle stage and process group (paste solder)

Life-cycle stage	**SnPb**		**SAC**		**BSA**		**SABC**	
Process group	Score*	%	Score*	%	Score*	%	Score*	%
UPSTREAM								
Sn production	2.63E-01	3.78	3.84E-01	5.45	1.97E-01	3.82	3.88E-01	5.96
Pb production	3.71E-02	0.534	N/A	N/A	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	1.62E+00	23.0	4.84E-01	9.40	1.04E+00	16.0
Cu production	N/A	N/A	5.25E-04	0.0074	N/A	N/A	4.39E-04	0.0067
Bi production	N/A	N/A	N/A	N/A	8.46E-02	1.64	1.28E-03	0.0197
Total	**3.00E-01**	**4.31**	**2.01E+00**	**28.4**	**7.65E-01**	**14.9**	**1.43E+00**	**22.0**
MANUFACTURING								
Solder manufacturing	2.66E-02	0.382	3.52E-02	0.500	2.42E-02	0.471	3.54E-02	0.543
Post-industrial recycling	8.98E-02	1.29	1.01E-01	1.43	3.67E-02	0.712	1.00E-01	1.54
Total	**1.16E-01**	**1.67**	**1.36E-01**	**1.93**	**6.09E-02**	**1.18**	**1.36E-01**	**2.08**
USE/APPLICATION								
Reflow application	5.09E+00	73.2	4.80E+00	68.1	3.97E+00	77.0	4.82E+00	74.1
Total	**5.09E+00**	**73.2**	**4.80E+00**	**68.1**	**3.97E+00**	**77.0**	**4.82E+00**	**74.1**
END-OF-LIFE								
Landfill	1.02E+00	14.7	4.82E-04	0.0068	1.43E-01	2.77	4.81E-03	0.0739
Incineration	2.81E-01	4.04	1.05E-02	0.149	6.91E-02	1.34	1.43E-02	0.220
Demanufacture	4.23E-04	0.0061	3.66E-04	0.0052	4.31E-04	0.0084	3.67E-04	0.0056
Cu smelting	1.23E-02	0.177	1.06E-02	0.150	N/A	N/A	1.08E-02	0.166
Unregulated	1.30E-01	1.87	8.79E-02	1.25	1.44E-01	2.80	9.01E-02	1.38
Total	**1.45E+00**	**20.8**	**1.10E-01**	**1.56**	**3.56E-01**	**6.92**	**1.20E-01**	**1.85**
GRAND TOTAL	**6.96E+00**	**100**	**7.05E+00**	**100**	**5.15E+00**	**100**	**6.51E+00**	**100**

*The impact scores are in units of kilograms cancertox-equivalents/1,000 cc of solder applied to a printed wiring board.
N/A=not applicable

In the manufacturing life-cycle stage, post-industrial recycling contributes more to total impacts than solder manufacturing. For all alloys, post-industrial recycling contributes between 0.71 and 1.5 percent; and solder manufacturing contributes between 0.38 and 0.54 percent of total impacts depending on the alloy.

Top Contributors to Public Health Impacts (Paste Solder)

Table 3-89 presents the specific materials or flows contributing greater than one percent of public *non-cancer* impacts by solder. As presented above, the SnPb impacts are dominated by the EOL stage. In particular, lead emissions to water, from both landfilling and incineration at the EOL stage, constitute about 91 percent of total SnPb life-cycle impacts combined. For both of these processes, lead emissions to water occur from landfill leachate (e.g., from leaching of waste electronics or incinerator ash). Sulphur dioxide emissions from electricity generation in the use/application stage are the next greatest contributors to SnPb public non-cancer impacts at about 3 percent, followed by lead emissions to air, water, and soil from unregulated recycling and disposal which all contribute less than 2 percent.

While the SnPb public health non-cancer impacts are dominated by EOL lead emissions, the lead-free alternatives are largely influenced by upstream metals production processes (e.g., silver, tin, and bismuth production) and electricity generation for reflow soldering. Specific flows that contribute greatly to impact scores include the following: sulphur dioxide from silver production (24 to 39 percent contribution); sulphur dioxide from electricity production for reflow soldering (25 to 41 percent contribution); and lead emissions to soil from silver production (18 to 29 percent). Smaller contributors are lead emissions to air from silver production, arsenic emissions to soil from silver production, and sulphur dioxide emissions from tin and bismuth production.

Table 3-89. Top contributors to public non-cancer impacts (paste solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	End-of-life	Solder landfilling (SnPb)	Lead emissions to water	72.6
	End-of-life	Solder incineration (SnPb)	Lead emissions to water	18.8
	Use/application	Electricity generation	Sulphur dioxide	3.19
	End-of-life	Unregulated recycling and disposal (SnPb)	Lead emissions to air	1.67
	End-of-life	Unregulated recycling and disposal (SnPb)	Lead emissions to soil	1.67
	End-of-life	Unregulated recycling and disposal (SnPb)	Lead emissions to water	1.12
SAC	Upstream	Silver production	Sulphur dioxide	38.7
	Upstream	Silver production	Lead emissions to soil	28.5
	Use/application	Electricity generation	Sulphur dioxide	25.0
	Upstream	Silver production	Lead emissions to air	2.05
	Upstream	Tin production	Sulphur dioxide	1.85
	Upstream	Silver production	Arsenic emissions to soil	1.11
BSA	Use/application	Electricity generation	Sulphur dioxide	41.2
	Upstream	Silver production	Sulphur dioxide	24.3
	Upstream	Silver production	Lead emissions to soil	17.9
	Upstream	Bismuth production	Sulphur dioxide	9.56
	Upstream	Tin production	Sulphur dioxide	1.99
	Upstream	Silver production	Lead emissions to air	1.29
SABC	Use/application	Electricity generation	Sulphur dioxide	33.7
	Upstream	Silver production	Sulphur dioxide	33.5
	Upstream	Silver production	Lead emissions to soil	24.6
	Upstream	Tin production	Sulphur dioxide	2.50
	Upstream	Silver production	Lead emissions to air	1.78

As discussed in detail in Section 3.2.11.2 (*Top Contributors to Occupational Impacts* section), human health impacts are derived from multiplying the inventory amount by the HV for a particular material. Lead has a high non-cancer toxicity HV (62,400), indicating that emissions of lead will have a higher non-cancer impact score than emissions of a less toxic substance when the output amount is the same. Further, lead has higher leachability than the other solder metals as evidenced by TCLP testing conducted in support of the LFSP. For example, the fraction of lead in SnPb that was found to leach is approximately 0.19, compared to a fraction of 0.000019 silver in SAC, and 0.000013 of copper in SAC (see Chapter 2 and Appendix C). These two factors are responsible for the SnPb impacts at EOL being far greater than the impacts from the other alloys.

The public non-cancer impact scores of the lead-free paste solders, on the other hand, are dominated somewhat by sulfur dioxide emissions (HV=660), and to a lesser extent by lead emissions from silver production. None of the lead-free solder metals themselves are top contributors to public non-cancer impacts, even though silver, with the second highest HV of any of the solder metals behind lead, has a relatively high HV of 10,000. This reveals that sulfur dioxide, which has a lower HV than silver, has a greater inventory amount than silver, and the metals in the lead-free solders are either not of high enough toxicity or enough quantity to be top contributors to the total impacts. The relatively high percent contributions of lead emissions from silver production to the total impacts of the lead-free solders are primarily due to lead’s high HV, rather than a large inventory amount.

Table 3-90 presents the specific materials or flows contributing at least 1 percent of public *cancer* impacts by solder. Nitrogen oxides from electricity generation needed for reflow application are the greatest contributors to public cancer impacts, ranging from 30 to 33 percent contribution to total impacts depending on the solder. Methane from electricity generation in the use/application stage also is a large contributor, ranging between about 14 and 15 percent. The relatively high public cancer impact scores for nitrogen oxides and methane are primarily due to their relatively large output flows from the extraction, processing, and consumption of fossil fuels to generate electricity. Since no cancer toxicity data were available for either of these materials, they were both assigned a default cancer HV of 1.

Table 3-90. Top contributors to public cancer impacts (paste solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	Use/application	Electricity generation	Nitrogen oxides	32.8
	End-of-life	Solder landfilling (SnPb)	Lead emissions to water	14.8
	Use/application	Electricity generation	Methane to air	14.6
	Use/application	Electricity generation	Carbon monoxide	5.52
	Use/application	Electricity generation	Dust (unspecified) to air	5.18
	End-of-life	Solder incineration (SnPb)	Lead emissions to water	3.84
	Use/application	SnPb (paste) reflow application	Flux material C *	3.17
	Use/application	SnPb (paste) reflow application	Flux material F *	2.64
	Use/application	SnPb (paste) reflow application	Flux material D *	2.64
	Upstream	Tin production	Nitrogen oxides	2.18
	Use/application	Electricity generation	NMVOC (unspecified) to air	1.67
	Use/application	SnPb (paste) reflow application	Flux material E *	1.59
	Upstream	Tin production	Dust (unspecified) to air	1.25
	Use/application	SnPb (paste) reflow application	Flux material A *	1.06

Table 3-90. Top contributors to public cancer impacts (paste solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SAC	Use/application	Electricity generation	Nitrogen oxides	30.4
	Use/application	Electricity generation	Methane to air	13.6
	Upstream	Silver production	Dust (unspecified) to air	11.9
	Use/application	Electricity generation	Carbon monoxide	5.12
	Use/application	Electricity generation	Dust (unspecified) to air	4.81
	Upstream	Tin production	Nitrogen oxides	3.15
	Use/application	SAC (paste) reflow application	Flux material C *	3.02
	Upstream	Silver production	Arsenic emissions to soil	2.82
	Use/application	SAC (paste) reflow application	Flux material F *	2.52
	Use/application	SAC (paste) reflow application	Flux material D *	2.52
	Upstream	Silver production	Methane to air	2.41
	Upstream	Silver production	Nitrogen oxides	2.03
	Upstream	Tin production	Dust (unspecified) to air	1.81
	Use/application	Electricity generation	NMVOC (unspecified) to air	1.55
	Use/application	SAC (paste) reflow application	Flux material E *	1.51
	Upstream	Silver production	Arsenic emissions to air	1.36
	Use/application	SAC (paste) reflow application	Flux material A *	1.01
BSA	Use/application	Electricity generation	Nitrogen oxides	32.4
	Use/application	Electricity generation	Methane to air	14.4
	Use/application	Electricity generation	Carbon monoxide	5.45
	Use/application	Electricity generation	Dust (unspecified) to air	5.12
	Upstream	Silver production	Dust (unspecified) to air	4.84
	Use/application	BSA (paste) reflow application	Flux material C *	4.35
	Use/application	BSA (paste) reflow application	Flux material F *	3.63
	Use/application	BSA (paste) reflow application	Flux material D *	3.63
	End-of-life	Solder landfilling (BSA)	Bismuth emissions to water	2.58
	Upstream	Tin production	Nitrogen oxides	2.20
	Use/application	BSA (paste) reflow application	Flux material E *	2.18
	Use/application	Electricity generation	NMVOC (unspecified) to air	1.65
	Use/application	BSA (paste) reflow application	Flux material A *	1.45
	End-of-life	Unregulated recycling and disposal (BSA)	Bismuth emissions to air	1.44
	Upstream	Tin production	Dust (unspecified) to air	1.26
	Upstream	Silver production	Arsenic emissions to soil	1.15
	End-of-life	Solder incineration (BSA)	Bismuth emissions to water	1.04
SABC	Use/application	Electricity generation	Nitrogen oxides	33.1
	Use/application	Electricity generation	Methane to air	14.8
	Upstream	Silver production	Dust (unspecified) to air	8.30
	Use/application	Electricity generation	Carbon monoxide	5.57
	Use/application	Electricity generation	Dust (unspecified) to air	5.23
	Upstream	Tin production	Nitrogen oxides	3.45
	Use/application	SABC (paste) reflow application	Flux material C *	3.28
	Use/application	SABC (paste) reflow application	Flux material F *	2.74
	Use/application	SABC (paste) reflow application	Flux material D *	2.74
	Upstream	Tin production	Dust (unspecified) to air	1.98
	Upstream	Silver production	Arsenic emissions to soil	1.97

Table 3-90. Top contributors to public cancer impacts (paste solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
	Use/application	Electricity generation	NMVOC (unspecified) to air	1.69
	Upstream	Silver production	Methane to air	1.68
	Use/application	SABC (paste) reflow application	Flux material E *	1.65
	Upstream	Silver production	Nitrogen oxides	1.42
	Use/application	SABC (paste) reflow application	Flux material A *	1.10

* Flux names have been removed to protect confidentiality.

For the SnPb alloy, lead outputs from landfilling contribute 15 percent of the total public cancer impact score for SnPb. The relatively high impact score for this flow is due to the fact that lead was found to leach substantially more than metals in the other alloys. The remaining top contributors for any of the alloys shown in Table 3-80 include several different flows, all of which contribute approximately 12 percent or less. These include carbon monoxide, dust, flux materials, arsenic, NMVOCs, and bismuth emissions. These emissions are from various processes and life-cycle stages.

Of interest is that arsenic is the only top material contributor to the public cancer impacts that is a known human carcinogen (cancer HV=29). The only other material that has been classified by EPA or IARC as to carcinogenicity is lead, which is a “probable human carcinogen.” As discussed previously (Section 3.2.11.1), the LFSP LCIA methodology assigns chemicals with a positive WOE classification, but no slope factor, a HV equal to 1, which is representative of an average HV. The methodology also assigns chemicals with no cancer toxicity data a HV of 1 to avoid the bias that typically favors chemicals with missing data. This was the case with all of the other top contributors to solder paste public cancer impacts, which were all assigned a HV of 1 due to missing data; therefore, much of the public cancer impacts are driven by a lack of data, rather than known carcinogenic hazards. This is particularly true for the lead-free alloys that are not affected by lead emissions. For SnPb, on the other hand, lead outputs contribute about 18.6 percent to the total impacts (for landfilling and incineration combined), and the lead HV is based on some carcinogenic rating, although the potential potency of lead as a carcinogen is not known. SnPb is *less* driven by a lack of data than the lead-free alloys; however, it is still highly driven by a lack of data given that all the remaining top contributors, aside from lead emissions, have no applicable carcinogenic data.

3.2.12.3 Bar solder results

Total Public Health Impacts by Life-Cycle Stage (Bar Solder)

Table 3-91 presents the bar solder results for public human health *non-cancer* impacts by life-cycle stage, based on the impact assessment methodology presented above. The table lists the public non-cancer impact scores per functional unit for the life-cycle stages of each bar solder alloy, as well as the percent contribution of each life-cycle stage to the total impacts. Figure 3-31 presents the results in a stacked bar chart.

Table 3-91. Public non-cancer impacts by life-cycle stage (bar solder)

Life-cycle stage	SnPb		SAC		SnCu	
	Score*	%	Score*	%	Score*	%
Upstream	1.84E+02	0.138	1.16E+04	94.7	2.20E+02	30.0
Manufacturing	5.28E+01	0.0394	1.95E+01	0.160	2.65E+01	3.62
Use/application	4.55E+02	0.339	4.65E+02	3.81	4.65E+02	63.4
End-of-life	1.33E+05	99.5	1.66E+02	1.36	2.16E+01	2.94
Total	**1.34E+05**	**100**	**1.22E+04**	**100**	**7.33E+02**	**100**

*The impact scores are in units of kg noncancertox-equivalents/1,000 cc of solder applied to a printed wiring board.

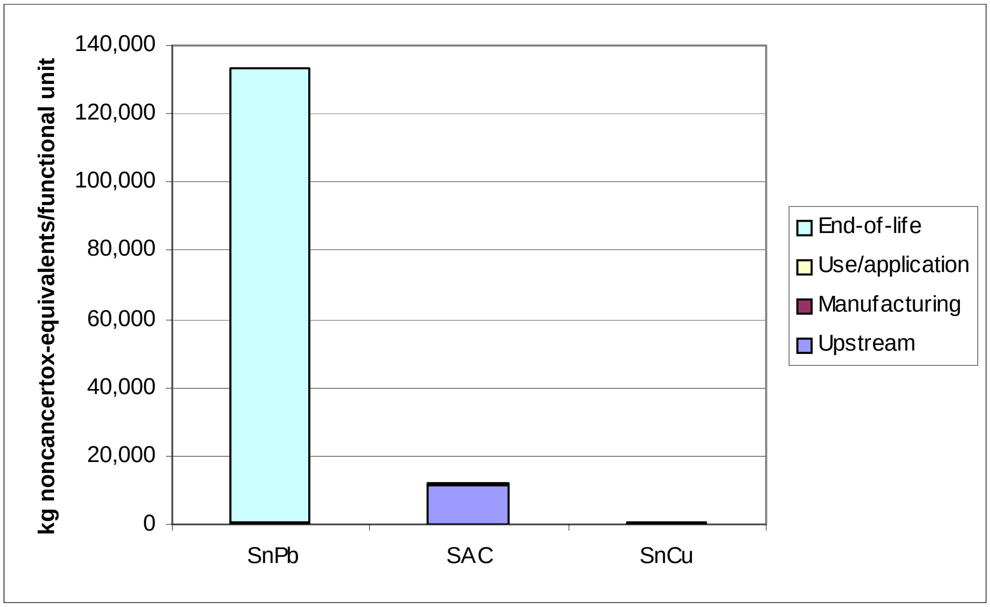

Figure 3-31. Bar Solder Total Life-Cycle Impacts: Public Non-Cancer

The public non-cancer impacts for SnPb (134,000 kg noncancertox-equivalents/functional unit) are far greater than the other alloys (12,200 and 733 kg noncancertox-equivalents/functional unit for SAC and SnCu, respectively). The EOL stage dominates impacts for SnPb, contributing 99.5 percent to the total SnPb public non-cancer impacts. The EOL impacts for the other alloys contribute only about 1 to 3 percent of total impacts. EOL public non-cancer impacts are much greater for SnPb than the other solders due to lead's high HV combined with its greater leachability as determined by TCLP testing (see Chapter 2 and Appendix C), which was discussed above in the paste solder results (3.2.12.2).

For the lead-free alternatives, the upstream life-cycle stage is the greatest contributor to overall public non-cancer impacts. SAC has the greatest upstream public non-cancer impacts at 11,600 kg noncancertox-equivalents/functional unit, which is 95 percent of total SAC public non-cancer impacts. SnCu has the greatest proportion of its impacts from the wave soldering use/application stage at 465 kg noncancertox-equivalents/functional unit or 63 percent contributions to total SnCu impacts. The upstream public non-cancer impacts for SnCu are 220 kg noncancertox-equivalents/functional unit or a contribution of 30 percent.

The use/application stage, which is made up of the wave soldering process group, is the second greatest contributor for SnPb and SAC and the greatest contributor for SnCu. Impacts from this life-cycle stage are associated with outputs from wave soldering (e.g., flux releases) and from the generation of electricity used to melt the bar solder for wave application, and are greatest for the alloys that consume the most energy during use. SAC and SnCu have slightly greater impacts from the use/application stage, both at 465 kg noncancertox-equivalents/functional unit, than does SnPb, 455 kg noncancertox-eqivalents/functional unit. The percent contribution of the use/application stage to SnPb total impacts is relatively small (3 percent) compared to the lead-free alloys (about 26 to 42 percent for SAC and BSA, respectively). This is due to lead's high HV which causes its impact scores at EOL to be much greater than SnPb impact scores from solder reflow (e.g., from outputs from electricity generation). Life-cycle public non-cancer impacts from the manufacturing stage are relatively small for all of the bar solder alloys, ranging from 19.5 to 52.8 kg noncancertox-equivalents/functional unit or about 0.04 to 4 percent of total impacts.

Table 3-92 presents the bar solder results for public human health *cancer* impacts by life-cycle stage, based on the impact assessment methodology presented above in Section 3.2.12.1. The table lists the public cancer impact scores per functional unit for the life-cycle stages of each bar solder alloy, as well as the percent contribution of each life-cycle stage to the total impacts. Figure 3-32 presents the results in a stacked bar chart.

Table 3-92. Public cancer impacts by life-cycle stage (bar solder)

Life-cycle stage	**SnPb**		**SAC**		**SnCu**	
	Score*	%	Score*	%	Score*	%
Upstream	2.88E-01	4.20	2.95E+00	23.7	4.18E-01	4.20
Manufacturing	2.66E-01	3.87	3.91E-01	3.15	4.32E-01	4.34
Use/application	3.41E+00	49.7	8.08E+00	65.0	8.07E-01	81.0
End-of-life	2.90E+00	42.3	1.01E+00	8.13	1.04E+00	10.5
Total	**6.87E+00**	**100**	**1.24E+01**	**100**	**9.96E+00**	**100**

*The impact scores are in units of kg cancertox-equivalents/1,000 cc of solder applied to a printed wiring board.

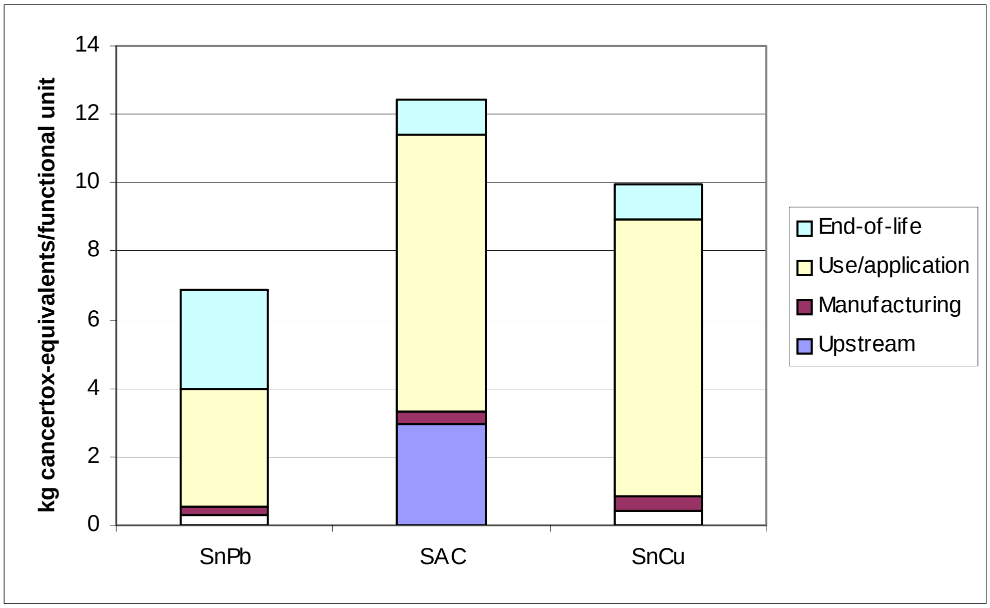

Figure 3-32. Bar Solder Total Life-Cycle Impacts: Public Cancer

SAC has the highest total public cancer impact score (12.4 kg cancertox-equivalents/functional unit), followed by SnCu and SnPb (9.96 and 6.87 kg cancertox-equivalents/functional unit, respectively). Impacts are dominated by wave soldering from the use/application life-cycle stage for all three bar solder alloys (50, 65, and 81 percent for SnPb, SAC, and SnCu, respectively). SnPb and SnCu have the second greatest proportion of their impacts from EOL (42 and 11 percent, respectively). The upstream stage is the second greatest contributor to SAC impacts (2.95 kg cancertox-equivalents/functional unit or 24 percent of total impacts). EOL and manufacturing stages are smaller contributors to SAC than the other life-cycle stages. For SnPb and SnCu, upstream and manufacturing are the smaller contributing stages.

Public Health Impacts by Process Group (Bar Solder)

Table 3-93 lists the public *non-cancer* impacts of each of the process groups in the life-cycle of the bar solders. Within the EOL stage of the SnPb life-cycle, landfilling is the greatest contributor to total impacts (54 percent of total public non-cancer impacts), followed by unregulated recycling/disposal (33 percent), and incineration (13 percent). Copper smelting and demanufacturing are very small contributors to the total SnPb public non-cancer toxicity impacts (0.0041 and 0.0002 percent, respectively).

EOL processes are much less significant to total public non-cancer impacts for the lead-free bar solder alloys. When evaluating these alloys alone, unregulated recycling and disposal is the greatest contributor to EOL impacts for SAC (163 kg noncancertox-equivalents/functional unit) and copper smelting is the greatest contributor to EOL impacts for SnCu (19.7 kg noncancertox-equivalents/functional unit). These process groups only contribute approximately 1.3 and 2.7 percent to the total scores, respectively. SnCu has the lowest unregulated recycling and disposal score because neither lead nor silver are in the alloy. The high toxicity values of lead and silver cause the unregulated recycling and disposal impacts for SnPb and SAC to be greater than those from SnCu.

For SAC, the silver production process in the upstream life-cycle stage is the process group with the greatest contribution to public non-cancer impacts, accounting for 92 percent of total impacts. The next greatest contributor within the upstream life-cycle stage for SAC is tin production (2.2 percent contribution). For SnCu, as expected based on mass composition, tin production is greatest (29 percent), followed by copper production (1.2 percent).

As noted previously, the wave solder application process is either the first or second greatest contributor to lead-free solder public non-cancer impacts within all the life-cycle stages, and there is only one process group within this life-cycle stage.

Table 3-93 also shows the contribution of two process groups—solder manufacturing and post-industrial recycling—within the manufacturing stage, which contribute a small proportion to the overall impacts for all of the solders. SAC and SnCu have similar impact scores for solder manufacturing (9.7 and 9.6 kg noncancertox-equivalents/functional unit, respectively), while the SnPb score is slightly lower (7.6 kg noncancertox-equivalents/functional unit). For the post-industrial recycling process group, impacts are greatest for SnPb (45 kg noncancertox-equivalents/functional unit), followed by SnCu and SAC (16.9 and 9.88 kg noncancertox-equivalents/functional unit, respectively). In each case, post-industrial recycling impacts are greater than solder manufacturing inputs which are driven by the post-industrial recycling process, as well as the secondary metal content of each alloy.

Table 3-94 lists the public *cancer* impacts of each of the process groups in the life-cycle of the bar solders. The impact scores from the use/application stage are predominately due to the flux materials released during wave soldering. Other contributions are from potentially carcinogenic outputs from electricity generation in the wave soldering process group.

EOL impacts arise from output flows of potentially carcinogenic materials released from the various EOL processes. For all the bar alloys, unregulated recycling and disposal has the highest EOL impact score, ranging from about 8 to 21 percent of total life-cycle impacts. For SnPb, landfilling is the second greatest contributing process group (about 17 percent of the total public cancer impact score). Incineration contributes 4 percent to the total SnPb public cancer impact score. For SAC and SnCu, the other processes aside from unregulated recycling and disposal contribute small proportions to the total impact scores.

Table 3-93. Public non-cancer impacts by life-cycle stage and process group (bar solder)

Life-cycle stage	**SnPb**		**SAC**		**SnCu**	
Process group	Score*	%	Score*	%	Score*	%
UPSTREAM						
Sn production	1.29E+02	0.0964	2.74E+02	2.24	2.11E+02	28.8
Pb production	5.52E+01	0.0412	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	1.13E+04	92.4	N/A	N/A
Cu production	N/A	N/A	9.13E+00	0.0749	8.96E+00	1.22
Total	**1.84E+02**	**0.138**	**1.16E+04**	**94.7**	**2.20E+02**	**30.3**
MANUFACTURING						
Solder manufacturing	7.63E+00	0.0057	9.67E+00	0.0792	9.58E+00	1.31
Post-industrial recycling	4.52E+01	0.0337	9.88E+00	0.0809	1.69E+01	2.31
Total	**5.28E+01**	**0.0394**	**1.95E+01**	**0.160**	**2.65E+01**	**3.62**
USE/APPLICATION						
Solder application	4.55E+02	0.339	4.65E+02	3.81	4.65E+02	63.4
Total	**4.55E+02**	**0.339**	**4.65E+02**	**3.81**	**4.65E+02**	**63.4**
END-OF-LIFE						
Landfill	7.10E+04	53.5	1.01E+00	0.0082	2.32E-02	0.0032
Incineration	1.80E+04	13.4	-6.70E-02	-0.0005	-3.17E-01	-0.0433
Demanufacture	3.12E-01	0.0002	2.73E-01	0.0022	2.71E-01	0.0370
Cu smelting	5.50E+00	0.0041	1.99E+00	0.0163	1.97E+01	2.68
Unregulated	4.37E+04	32.6	1.63E+02	1.34	1.93E+00	0.264
Total	**1.33E+05**	**99.5**	**1.66E+02**	**1.36**	**2.16E+01**	**2.94**
GRAND TOTAL	**1.34E+05**	**100**	**1.22E+04**	**100**	**7.33E+02**	**100**

*The impact scores are in units of kg noncancertox-equivalents/1,000 cc of solder applied to a printed wiring board.
N/A=not applicable

Potential upstream impacts arise from outputs of potentially carcinogenic materials in the extraction and processing of the various metals present in the alloys. With the bar solder alloys, the public cancer impact scores from tin extraction and processing comprise between about 3.7 and 4.2 percent of the total; for SnPb, about 0.48 percent of impacts are from lead extraction and processing; and for SnCu about 0.0086 percent for copper extraction and processing. For SAC, silver production dominates upstream impacts, contributing about 19 percent to the total score. Public cancer impacts from silver processing exceed impacts from tin processing in solders that contain both metals, even though the silver content of the alloys is much less than the tin content. As described in earlier sections, SAC is 95.5 percent tin and only 3.9 percent silver, yet its impacts from silver production are greater than those from tin production. This indicates that potential cancer impacts from silver extraction and processing outputs are disproportionately high compared to the other solder metals.

In the manufacturing life-cycle stage of SnPb, post-industrial recycling contributes slightly more to total impacts than does solder manufacturing. For the lead-free alloys, solder manufacturing contributes more than does post-industrial recycling. SAC solder manufacturing contributes 2.7 percent compared to SAC post-industrial recycling, which contributes 0.49

percent. SnCu solder manufacturing contributes about 3.3 percent compared to about 1.1 percent for post-industrial recycling. This is because there is more recycled metal content in SnPb than for SAC and SnCu.

Table 3-94. Public cancer impacts by life-cycle stage and process group (bar solder)

Life-cycle stage	**SnPb**		**SAC**		**SnCu**	
Process group	Score*	%	Score*	%	Score*	%
UPSTREAM						
Sn production	2.55E-01	3.72	5.40E-01	4.35	4.17E-01	4.19
Pb production	3.31E-02	0.483	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	2.41E+00	19.3	N/A	N/A
Cu production	N/A	N/A	8.76E-04	0.0070	8.60E-04	0.0086
Total	**2.88E-01**	**4.20**	**2.95E+00**	**23.7**	**4.18E-01**	**4.20**
MANUFACTURING						
Solder manufacturing	1.14E-01	1.67	3.30E-01	2.66	3.28E-01	3.29
Post-industrial recycling	1.51E-01	2.20	6.08E-02	0.489	1.04E-01	1.05
Total	**2.66E-01**	**3.87**	**3.91E-01**	**3.15**	**4.32E-01**	**4.34**
USE/APPLICATION						
Solder application	3.41E+00	49.7	8.08E+00	65.0	8.07E+00	81.0
Total	**3.41E+00**	**49.7**	**8.08E+00**	**65.0**	**8.07E+00**	**81.0**
END-OF-LIFE						
Landfill	1.15E+00	16.7	5.41E-04	0.0044	5.65E-04	0.0057
Incineration	2.96E-01	4.31	1.12E-02	0.0903	1.16E-02	0.117
Demanufacture	4.70E-04	0.0068	4.11E-04	0.0033	4.08E-04	0.0041
Cu smelting	1.37E-02	0.199	1.19E-02	0.0958	1.18E-02	0.119
Unregulated	1.44E+00	21.0	9.87E-01	7.94	1.02E+00	10.2
Total	**2.90E+00**	**42.3**	**1.01E+00**	**8.13**	**1.04E+00**	**10.5**
GRAND TOTAL	**6.87E+00**	**100**	**1.24E+01**	**100**	**9.96E+00**	**100**

*The impact scores are in units of kg cancertox-equivalents/1,000 cc of solder applied to a printed wiring board.
N/A=not applicable

Top Contributors to Public Health Impacts (Bar Solder)

Table 3-95 presents the specific materials or flows contributing greater than 1 percent of public *non-cancer* impacts by bar solder. As presented above, the SnPb impacts are dominated by the EOL stage. In particular, lead emissions to water, from both landfilling and incineration at EOL constitute about 66 percent of the total SnPb life-cycle impacts combined. For both of these processes, lead emissions to water occur from landfill leachate (i.e., from leaching of waste electronics or incinerator ash). Lead emissions to air, soil, and water from unregulated recycling and disposal are the next greatest contributors (12, 12, and 8.2 percent, respectively); these are from direct releases to the environment.

Table 3-95. Top contributors to public non-cancer impacts (bar solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	End-of-life	Solder landfilling (SnPb)	Lead to water	53.3
	End-of-life	Solder incineration (SnPb)	Lead to water	13.1
	End-of-life	Unregulated recycling and disposal (SnPb)	Lead to air	12.3
	End-of-life	Unregulated recycling and disposal (SnPb)	Lead to soil	12.3
	End-of-life	Unregulated recycling and disposal (SnPb)	Lead to water	8.19
SAC	Upstream	Silver production	Sulphur dioxide to air	49.6
	Upstream	Silver production	Lead to soil	36.5
	Use/application	Electricity generation	Sulphur dioxide to air	3.68
	Upstream	Silver production	Lead to air	2.63
	Upstream	Tin production	Sulphur dioxide to air	2.24
	Upstream	Silver production	Arsenic to soil	1.43
	End-of-life	Unregulated recycling and disposal (SAC)	Silver to water	1.32
SnCu	Use/application	Electricity generation	Sulphur dioxide to air	61.9
	Upstream	Tin production	Sulphur dioxide to air	29.1
	Manufacturing	Electricity generation for post-industrial recycling	Sulphur dioxide to air	2.19
	End-of-life	Post-consumer copper smelting (SnCu)	Copper to air	1.20
	End-of-life	Post-consumer copper smelting (SnCu)	Copper to soil	1.20
	Upstream	Copper production	Sulphur dioxide to air	1.18
	Manufacturing	Electricity generation for solder manufacturing	Sulphur dioxide to air	1.09

While the SnPb public health non-cancer impacts are dominated by EOL lead emissions, SAC is largely influenced by upstream metals production processes. Specific flows that contribute greatly to the SAC impact scores include sulphur dioxide from silver production (50 percent contribution) and lead emissions to soil from silver production (about 37 percent). Smaller contributors are sulphur dioxide from electricity generation for wave soldering, lead emissions to air from silver production, sulphur dioxide emissions from tin production, arsenic emissions to soil from silver production, and silver emissions to water from unregulated recycling and disposal.

Sulphur dioxide emissions from electricity generation in the use/application stage are the top contributor to SnCu public non-cancer impacts at about 62 percent, followed by sulphur dioxide emissions to air from tin production at 29 percent. Other top contributors are sulphur dioxide and copper to air from various processes in a mix of life-cycle stages.

As discussed in detail in Section 3.2.11.2 in the *Top Contributors to Public Health Impacts*, human health impacts are derived from multiplying the inventory amount by the HV for a particular material. Lead has a high non-cancer toxicity HV (about 62,400), indicating that emissions of lead will have a higher non-cancer impact score than emissions of a less toxic substance when the output amount is the same. Lead has higher leachability than the other solder metals as well, as evidenced by TCLP testing conducted in support of the LFSP. For example, a fraction of lead in SnPb that was found to leach is 0.19, compared to a fraction of 0.000019 silver in SAC, and a fraction of 0.000013 copper in SAC (see Chapter 2 and Appendix C). These two factors are responsible for the SnPb impacts at EOL being far greater than the impacts from the other alloys.

The public non-cancer impact scores of the lead-free bar solders, on the other hand, are dominated somewhat by sulphur dioxide emissions (HV=660), and to a lesser extent (for SAC), by lead emissions from silver production. The results suggest that sulphur dioxide, which has a lower HV than silver's 10,000 HV, has a greater inventory amount than silver, and that the metals in the lead-free solders are either not of a high enough toxicity or not enough quantity to exceed the impacts from sulphur dioxide. The relatively high percent contributions of lead emissions from silver production to the total impacts of SAC are primarily due to lead's high HV, rather than a large inventory amount.

Table 3-96 presents the specific materials or flows contributing at least 1 percent of public *cancer* impacts by bar solder. The top contributor to public cancer impacts for each bar alloy is flux from wave application in the use/application stage. For the SnPb bar solder alloy, flux material "F" contributes approximately 26 percent of total public impact score. (Note, letters are used in place of flux chemical names to protect confidentiality of companies that supplied the data.) The second greatest contributor to SnPb impacts are lead outputs to water from landfilling that contribute 17 percent to total public cancer impacts. The relatively high impact score for this flow is due to the fact that lead was found to leach substantially more than the metals in the other alloys (see Chapter 2 and Appendix C). Flux E from the wave application is the third greatest contributor to SnPb cancer impacts at 15 percent. The remaining top contributors for SnPb shown in Table 3-86 include several different flows, all of which contribute approximately 7 percent or less. These include tin to water, nitrogen oxides to air, lead to air and soil, methane to air, and dust to air. These emissions are from various processes and life-cycle stages as shown in the table.

Table 3-96. Top contributors to public cancer impacts (bar solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	Use/application	SnPb (bar) wave application	Flux material F *	25.5
	End-of-life	Solder landfilling (SnPb)	Lead to water	17.2
	Use/application	SnPb (bar) wave application	Flux material E *	15.3
	End-of-life	Unregulated recycling and disposal (SnPb)	Tin to air	6.68
	Use/application	Electricity generation	Nitrogen oxides to air	5.36
	End-of-life	Unregulated recycling and disposal (SnPb)	Tin to water	4.45
	End-of-life	Solder incineration (SnPb)	Lead to water	4.18
	End-of-life	Unregulated recycling and disposal (SnPb)	Lead to air	3.92
	End-of-life	Unregulated recycling and disposal (SnPb)	Lead to soil	3.92
	End-of-life	Unregulated recycling and disposal (SnPb)	Lead to water	2.62
	Use/application	Electricity generation	Methane to air	2.39
	Upstream	Tin production	Nitrogen oxides to air	2.18
	Upstream	Tin production	Dust (unspecified) to air	1.25
SAC	Use/application	SAC (bar) wave application	Flux material C *	16.9
	Use/application	SAC (bar) wave application	Flux material F *	14.1
	Use/application	SAC (bar) wave application	Flux material D *	14.1
	Upstream	Silver production	Dust (unspecified) to air	10.2
	Use/application	SAC (bar) wave application	Flux material E *	8.46
	Use/application	SAC (bar) wave application	Flux material A *	5.66
	End-of-life	Unregulated recycling and disposal (SnAgCu)	Tin to air	4.90

Table 3-96. Top contributors to public cancer impacts (bar solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
	End-of-life	Unregulated recycling and disposal (SnAgCu)	Tin to water	3.27
	Use/application	Electricity generation	Nitrogen oxides to air	3.00
	Upstream	Tin production	Nitrogen oxides to air	2.56
	Upstream	Silver production	Arsenic to soil	2.42
	Upstream	Silver production	Methane to air	2.07
	Use/application	SAC (bar) wave application	Flux material B *	1.94
	Upstream	Silver production	Nitrogen oxides to air	1.74
	Upstream	Tin production	Dust (unspecified) to air	1.47
	Use/application	Electricity generation	Methane to air	1.34
	Upstream	Silver production	Arsenic to air	1.17
SnCu	Use/application	SnCu (bar) wave application	Flux material C *	21.3
	Use/application	SnCu (bar) wave application	Flux material D *	17.7
	Use/application	SnCu (bar) wave application	Flux material F *	17.7
	Use/application	SnCu (bar) wave application	Flux material E *	10.7
	Use/application	SnCu (bar) wave application	Flux material A *	7.08
	End-of-life	Unregulated recycling and disposal (SnCu)	Tin to air	6.38
	End-of-life	Unregulated recycling and disposal (SnCu)	Tin to water	4.25
	Use/application	Electricity generation	Nitrogen oxides to air	3.78
	Upstream	Tin production	Nitrogen oxides to air	2.49
	Use/application	SnCu (bar) wave application	Flux material B *	2.43
	Use/application	Electricity generation	Methane to air	1.68
	Upstream	Tin production	Dust (unspecified) to air	1.43

* Flux names have been removed to protect confidentiality.

The top three contributors to bar SAC cancer impacts are three fluxes from wave application that, when combined, constitute about 45 percent of the total public cancer impacts for SAC. The fourth top contributor is dust from silver production (10 percent). The remaining top contributors each contribute 8 percent or less. The top five contributors to bar SnCu cancer impacts are fluxes from wave application, which combined constitute 74 percent of total impacts. The remaining individual contributors contribute 6 percent or less, and are from various processes and life-cycle stages as shown in the table.

Arsenic is the only top material contributor to the public cancer impacts that is a known human carcinogen (cancer HV=29). The only other material that has been classified by EPA or IARC as to carcinogenicity is lead, which is a probable human carcinogen. As discussed previously, the LFSP LCIA methodology assigns chemicals with a positive WOE classification, but no slope factor, a HV equal to 1, which is representative of an average HV. The methodology also assigns chemicals with no cancer toxicity data a HV of 1 to avoid the bias that typically favors chemicals with missing data. This was the case with all of the other top contributors to solder paste public cancer impacts, which were all assigned a HV of 1 due to missing data; therefore, much of the public cancer impacts are driven by a lack of data, rather than known carcinogenic hazards. This is particularly true for the lead-free alloys, which are not affected by lead emissions. For SnPb, on the other hand, of the top contributors in Table 3-96, lead outputs contribute about 32 percent to the total impacts (for landfilling, incineration, and unregulated recycling/disposal combined), and the lead HV is based on some carcinogenic rating, although the potential potency of lead as a carcinogen is not known; therefore, SnPb is *less* driven by a lack of data than the lead-free alloys. It is still highly driven by a lack of data given that all of the remaining top contributors, aside from lead emissions, have no applicable carcinogenic data.

3.2.12.4 Limitations and uncertainties

This section summarizes the limitations and uncertainties associated with public non-cancer and cancer health impacts. The public health LCIA limitations and uncertainties that address (1) structural or modeling limitations and (2) toxicity data limitations, are identical to those for occupational health impacts. For a detailed discussion, refer to Section 3.2.11.4. For example, much of the public *cancer* impact results are driven by a lack of toxicity data, rather than known carcinogenic hazards. In addition, the LCI data limitations for public health impacts in many cases are similar to those described in Section 3.2.11.4. LCI data limitations pertinent to public health impacts are summarized below.

For SnPb, the EOL impacts dominate non-cancer total impacts for both paste and bar solder results, and cancer impacts also are somewhat influenced by EOL. The limitations and uncertainties for SnPb are most influenced by the EOL uncertainties and limitations. Public health impacts are based on process outputs as opposed to occupational impacts that are based on process inputs. The EOL outputs have uncertainties associated with the inventory quantities as they were based on assumptions about partitioning of the metals to various media, depending on the EOL process. Details of the limitations and uncertainties for outputs from each of the EOL processes are presented in Chapter 2, which provides limitations and uncertainties in the EOL inventory.

To summarize, for landfilling there is relatively low uncertainty associated with the leachability testing data used to calculate metal outputs from the landfill process, which are primary data collected for the purposes of the LFSP. Uncertainties do exist and are associated with (1) the TCLP test method itself and its representativeness of actual landfill conditions, and (2) the analytical method (for example, limitations in analytical detection limits and quality uncertainties associated with laboratory blanks). These limitations and uncertainties are discussed in more detail in Chapter 2, which summarizes the leachability results, and in Appendix C, which presents the leachability report. To address concerns that the TCLP test method is not representative of actual landfill conditions (i.e., it overstates the leachability of lead), a bounding analysis has been conducted that uses a lower bound of lead leachability to help determine the sensitivity of the results to the leachability data (see Section 3.3).

For incineration, secondary literature was reviewed to make assumptions about metal releases and partitioning to various environmental media. This introduced slightly more uncertainty into the incineration outputs than is expected with the landfilling data. Uncertainties associated with unregulated recycling and disposal are due to the almost complete absence of analytical data on the partitioning of metals among environmental media for these processes. EPA is currently conducting trials to assess metal emissions from open burning of electronics waste. These data could be used later to reassess the assumptions used here for unregulated recycling and disposal processes.

Uncertainties from copper smelting have less effect on the results as this process contributes small proportions to the total impacts. Nonetheless, uncertainties associated with copper smelting arise from the inability of the researchers to get direct quantitative data from primary data sources. Conversations with primary data suppliers and literature reviews, led to assumptions that are believed to be reasonable to predict outputs; therefore, uncertainty is considered to be acceptable for copper smelting outputs.

In addition to metal output uncertainties, there are EOL uncertainties related to the assumptions about EOL dispositions (e.g., 72 percent of solder goes directly to landfilling for SnPb, SAC, SABC, and SnCu). These are discussed in greater detail in Chapter 2.

Public health impacts of the lead-free alloys are generally dominated by the upstream and use/application life-cycle stages. The uncertainties associated with these stages affect the uncertainties for these alloys more so than the EOL uncertainties discussed above. Upstream uncertainties stem from the use of secondary data sources. Silver production, which accounts for a large proportion of the total public non-cancer impacts for the silver-bearing solders, has associated uncertainties that are described in Section 3.2.1.4. As presented in that section, although the secondary silver data set are considered “good” by GaBi, an alternate silver inventory (from DEAM) is used to assess the sensitivity of LCIA results to silver production data (see Section 3.3).

The use/application limitations and uncertainties related to electricity generation for paste reflow soldering outputs arise from two issues: (1) electricity generation outputs are based on the amount of electrical power used in the reflow solder process that was determined based on two primary data points for reflow energy covering a large range in energy, and (2) electricity production data are from a secondary source. Electricity consumption in the use/application stage is evaluated in a sensitivity analysis for paste results (see Section 3.3). For a more detailed discussion, refer to Section 3.2.1.4. Uncertainties from electricity use during bar solder wave application relate to the use of secondary electricity generation data, but the reflow energy uncertainty mentioned above does not apply.

Other uncertainties related to wave and reflow application relate to the assumption that all the flux materials, either in the paste or as applied during wave soldering, are volatilized and released to the environment. Primary data were not available on the capture of these materials or on the actual releases to the environment; therefore, the assumption that all the flux materials are released into the environment is an upper bound estimate for flux emissions to air, and a source of uncertainty in the application processes. This is mostly relevant to the human health cancer impacts for bar solders, each of which have a flux as their highest top contributor to total cancer impacts.

Given that the lead toxicity is such an important driver of public non-cancer impacts, further investigation into the impact score results has been done. For non-cancer impacts, the LCIA methodology employed in this study calculates HVs based on either inhalation or oral NOAELs or LOAELs. For chemicals that do not have NOAELs, LOAELs are used as the basis of the toxicity hazard value. If a chemical has both an inhalation and oral NOAEL, the toxicity value that results in the higher toxicity is chosen. This is a simple screening methodology that allows for many chemicals through various transport and exposure pathways to be considered in an analysis. The disadvantage of such a screening method is that it is applied to a variety of chemicals with various potential exposure scenarios (as is the case in an LCA), and the actual toxicity and exposure for any one particular chemical in a particular process may not be accurately represented. This method simply identifies chemicals of concern based on the most toxic exposure pathway for that chemical without regard to the specific pathway in a particular process. The reason this method uses either inhalation or oral toxicity data is because it is far too cumbersome to select a particular route of exposure for every chemical in every process in the life-cycle analysis; however, given that the lead toxicity is such an important driver of public non-cancer health impacts, further understanding and resolution of the data is warranted.

The lead non-cancer HV in the LCIA methodology employed in this study is based on an *inhalation* LOAEL. Of the top contributors in Table 3-95 and Table 3-96, 93 percent of the paste results and 75 percent of the bar results were from lead emissions to *water*. To identify what the results might look like if an *oral* NOAEL were used, an alternate analysis is presented here. Note, however, that this is not consistent with the methodology employed throughout all the life-cycle stages, which uses the most toxic NOAEL or LOAEL, regardless of the route of exposure. While an oral NOAEL might represent a more accurate exposure pathway for most of the EOL releases, it may not do so for other processes represented in the analysis. Because lead released to water is a large proportion of impacts, it seems worthy to estimate the sensitivity of the results to the inhalation NOAEL by conducting the analysis with an oral NOAEL for lead.

In the baseline case, the non-cancer HV for lead is 62,427, which is based on an inhalation LOAEL of 0.011 mg/m^3 (ATSDR, 1999), which is calculated to be equivalent to a NOAEL of 0.0011 mg/m^3. In the alternative case, the non-cancer HV is 10,000, based on an oral NOAEL of 0.0015 mg/kg-day (ATSDR, 1999). The HVs are calculated using equations presented in Section 3.2.11.1. Figures 3-33 and 3-34 show the comparative results for the non-cancer impacts using different lead toxicity non-cancer HVs for both the paste and bar solders, respectively. The results from the alternate analysis, which is based on the oral NOAEL, have the same conclusions for both the paste and bar analyses as they had for the baseline analyses; that is, SnPb remains the highest impact score, by a much smaller margin for the alternative analysis compared to the baseline. For the paste results, SnPb impacts were 7.6 times greater than SAC in the baseline case, and SnPb was 2.1 times greater than SAC in the alternative case. In both cases, EOL remained the top contributor, but to a lesser degree in the alternate case. In the baseline case, EOL contributed 96 percent to total impacts. With the oral-based HV, EOL comprised 82 percent of the total impacts.

For bar solder results, SnPb was 10.9 times greater than SAC in the baseline case (inhalation-based HV) and 2.7 times greater than SAC in the alternate case. In the baseline, EOL contributed 99 percent to total impacts, and in the alternate case, EOL contributed 97 percent to total impacts.

It is important to reiterate that by changing only the lead HV, we are not being consistent in how other chemicals are treated; therefore, this analysis should *not* be construed as a reasonable analysis to replace the baseline analysis. It is simply conducted to determine how the results are impacted given a change in only the lead non-cancer HV.

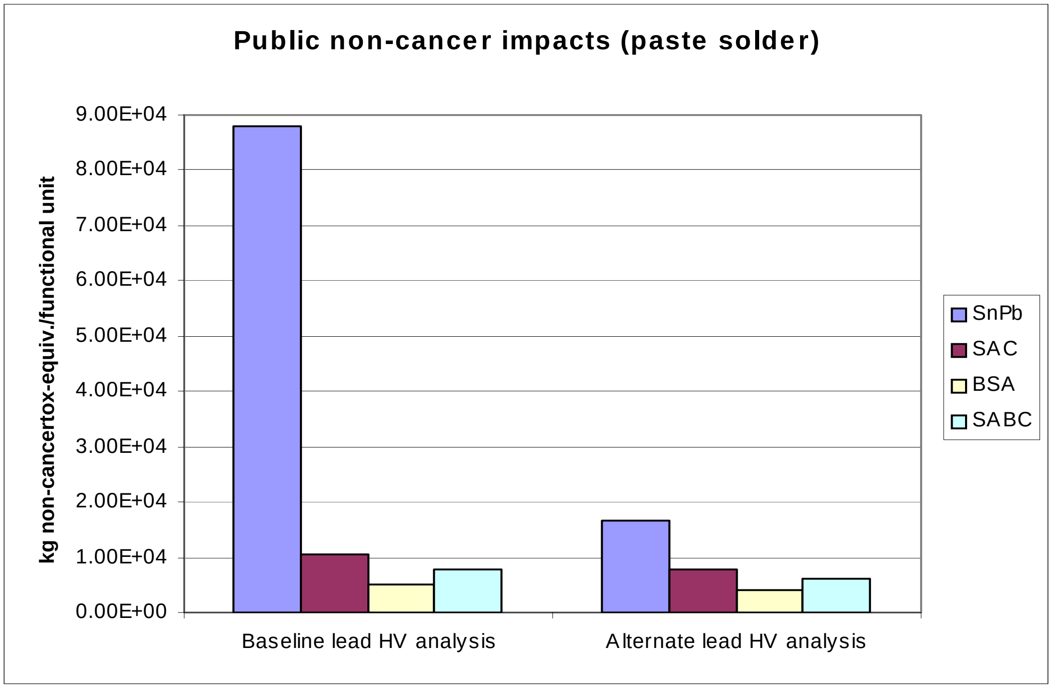

Figure 3-33. Comparative lead HV analysis (paste solder)

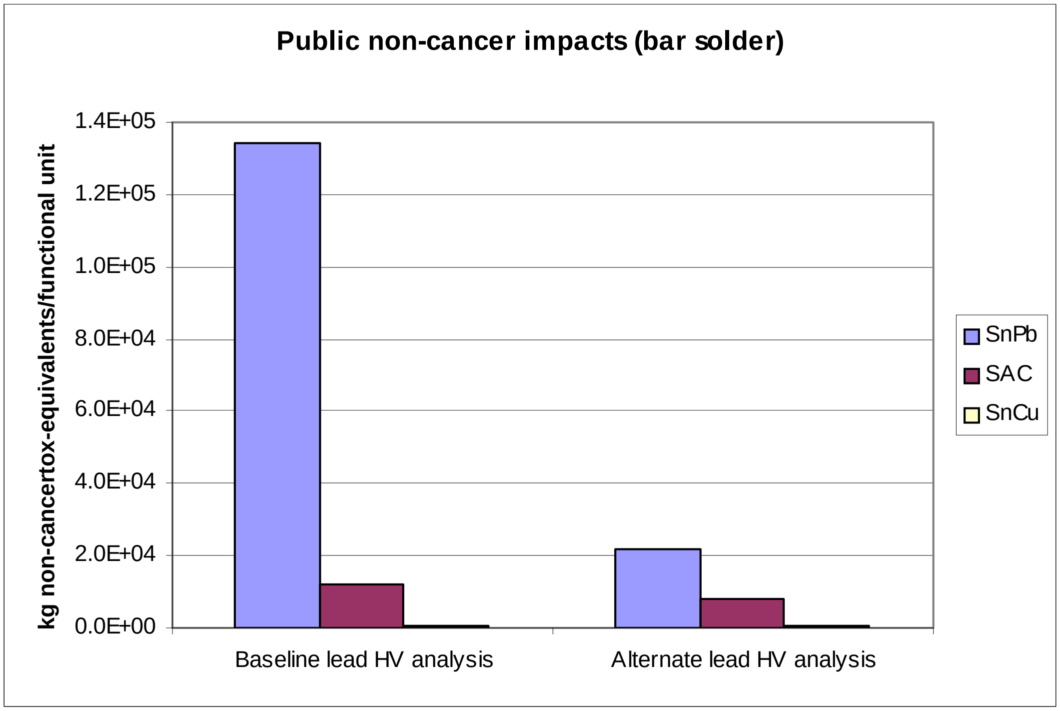

Figure 3-34. Comparative lead HV analysis (bar solder)

3.2.13 Aquatic Ecotoxicity Impacts

3.2.13.1 Characterization

Ecotoxicity refers to effects of chemical outputs on non-human living organisms. Impact categories could include both ecotoxicity impacts to aquatic and terrestrial ecosystems. The method for calculating terrestrial toxicity, however, would be the same as for the chronic, non-cancer public toxicity impacts described above, which are based on mammalian toxicity data. As the relative ranking approach of the LCIA toxicity method does not modify the toxicity data for different species or for fate and transport, both human and terrestrial LCIA impacts are the same; therefore, only aquatic toxicity, which uses a different methodology, is presented below.

Toxicity measures for fish are used to represent potential adverse effects to organisms living in the aquatic environment from exposure to a toxic chemical. Impact scores are based on the identity and amount of toxic chemicals as outputs to surface water. Impact characterization is based on CHEMS-1 acute and chronic hazard values for fish (Swanson *et al.*, 1997) combined with the inventory amount. Both acute and chronic impacts comprise the aquatic ecotoxicity term. The HVs for acute and chronic toxicity are based on LC_{50} (the lethal concentration to 50 percent of the exposed fish population) and NOEL (no-observed-effect level) (or NOEC [no-observed-effect concentration]) toxicity data, respectively, mostly from toxicity tests in fathead minnows (*Pimephales promelas*) (Swanson *et al.*, 1997). The acute fish HV is calculated by:

$$(HV_{FA})_i = \frac{1/(LC_{50})_i}{1/(LC_{50})_{mean}}$$

where:

HV_{FA}	equals the hazard value for acute fish toxicity for chemical *i* (unitless);
LC_{50}	equals the lethal concentration to 50 percent of the exposed fish population for chemical *i*; and
$LC_{50\ mean}$	equals the geometric mean LC_{50} of available fish LC_{50} values in Appendix E (24.6 mg/L).

The chronic fish HV is calculated by:

$$(HV_{FC})_i = \frac{1/NOEL_i}{1/NOEL_{mean}}$$

where:

HV_{FC} equals the hazard value for chronic fish toxicity for chemical *i*;

$NOEL$ equals the no-observed-effect level for fish for chemical *i*; and

$NOEL_{mean}$ equals the geometric mean NOEL of available fish NOEL values in Appendix D (3.9 mg/L).

For chemicals that do not have chronic fish toxicity data available, but do have LC_{50} data, the LC_{50} and the log K_{ow} of the chemical are used to estimate the NOEL. Based on studies comparing the LC_{50} to the NOEL (Kenega, 1982; Jones and Schultz, 1995, and Call *et al.*, 1985) as reported in Swanson *et al.* (1997), NOEL values for organic chemicals within a certain range of log K_{ow} values are calculated using the following continuous linear function:

For organics with $2 \# \log K_{ow} < 5$:

$$NOEL = LC_{50}/(5.3\ x \log K_{ow} - 6.6)$$

Organic chemicals with high log K_{ow} values (i.e., greater than 5) are generally more toxic to fish and are not expected to follow a continuous linear function with K_{ow}, thus, they are estimated directly from the LC_{50}. In addition, inorganic chemicals are poorly fat soluble and their fish toxicity does not correlate to log K_{ow}. The NOEL values of the inorganic chemicals were, therefore, also based on the fish LC_{50} values.

For inorganics or organics with $\log K_{ow} \$ 5$:

$$NOEL = 0.05\ x\ (LC_{50})$$

For organics with log $K_{ow}<2$, which are poorly fat soluble but assumed to have a higher NOEL value than those with higher K_{ow} values or than inorganics, the NOEL is estimated as follows:

For organics with $\log K_{ow} < 2$:

$$NOEL = 0.25\ x\ (LC_{50})$$

Once the HVs are calculated, whether from NOEL data or estimated from the LC_{50} and the K_{ow}, the aquatic toxicity impact score is calculated as follows:

$$(IS_{AQ})_i = [(HV_{FA} + HV_{FC})\ x\ Amt_{TCoutput,water}]_i$$

where:

IS_{AQ}	equals the impact score for aquatic ecotoxicity for chemical *i* (kg aquatictox-equivalent) per functional unit;
HV_{FA}	equals the hazard value for acute fish toxicity for chemical *i* (unitless);
HV_{FC}	equals the hazard value for chronic fish toxicity for chemical *i*; and,
$Amt_{TC\ output,water}$	equals the toxic inventory output amount of chemical *i* to water (kg) per functional unit.

3.2.13.2 Paste solder results

Total Aquatic Ecotoxicity Impacts by Life-Cycle Stage (Paste Solder)

Table 3-97 presents the solder paste results for aquatic ecotoxicity impacts by life-cycle stage, based on the impact assessment methodology presented above. The table lists the aquatic ecotoxicity impact scores per functional unit for the life-cycle stages of each solder paste alloy, as well as the percent contribution of each life-cycle stage to the total impacts. Figure 3-35 presents the results in a stacked bar chart.

Table 3-97. Aquatic ecotoxicity impacts by life-cycle stage (paste solder)

Life-cycle stage	**SnPb**		**SAC**		**BSA**		**SABC**	
	Score*	%	Score*	%	Score*	%	Score*	%
Upstream	1.07E-01	0.0084	1.85E+01	50.9	5.96E+00	25.5	1.19E+01	31.0
Manufacturing	1.61E-01	0.0126	5.88E-02	0.162	3.40E-02	0.145	5.90E-02	0.153
Use/application	1.49E+00	0.117	1.40E+00	3.84	1.09E+00	4.68	1.40E+00	3.65
End-of-life	1.27E+03	99.9	1.64E+01	45.1	1.63E+01	69.7	2.51E+01	65.2
Total	**1.27E+03**	**100**	**3.64E+01**	**100**	**2.34E+01**	**100**	**3.85E+01**	**100**

*The impact scores are in units of kilograms aquatictox-equivalents/1,000 cc of solder applied to a printed wiring board.

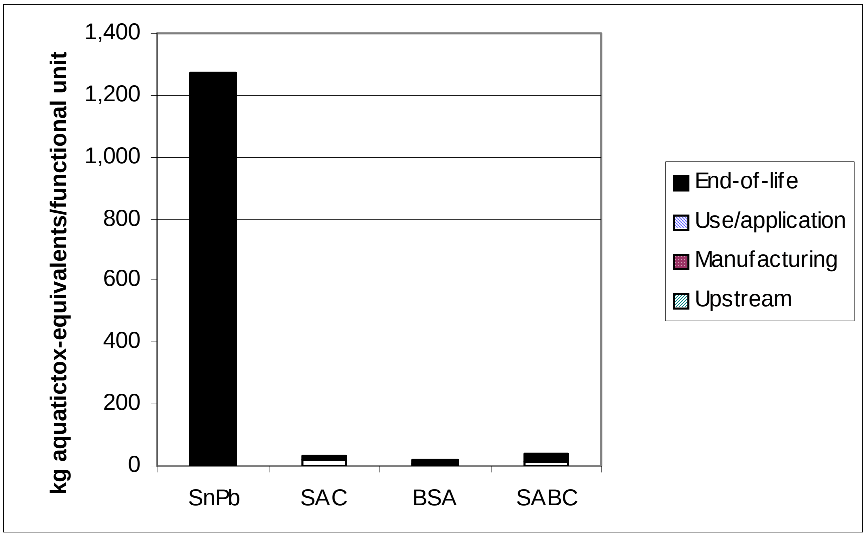

Figure 3-35. Solder Paste Total Life-Cycle Impacts: Aquatic Ecotoxicity

The total aquatic ecotoxicity impact score for SnPb (1,270 kg aquatictox-equivalents/functional unit) is far greater than the other solder paste alloys. SABC has the next greatest impact score (38.5 kg aquatictox-equivalents/functional unit), which is only slightly greater than that of SAC (36.4 kg aquatictox-equivalents/functional unit). BSA has the lowest aquatic ecotoxicity score of all the alloys (23.4 kg aquatictox-equivalents/functional unit).

The EOL stage accounts for nearly all of the SnPb impacts, contributing 99.9 percent to the total aquatic ecotoxicity impact score; however, EOL only accounts for about 45 to 70 percent of total impacts for the lead-free solders. For these alloys, the upstream life-cycle stage also is substantial contributor to total impacts (26 to 51 percent). SAC has the greatest upstream aquatic ecotoxicity impact score at 18.5 kg aquatictox-equivalents/functional unit, which is 51 percent the of total SAC aquatic ecotoxicity impacts. SABC has an upstream aquatic ecotoxicity impact score of 11.9 kg aquatictox-equivalents/functional unit, which contributes 31 percent of SABC's total impacts. BSA has a smaller upstream aquatic ecotoxicity impact score of 5.96 kg aquatictox-equivalents/functional unit, which is 26 percent of BSA's total impacts.

The use/application stage, which is comprised of the reflow soldering process and the associated generation of electricity, is the third greatest contributor for the lead-free alloys. Their aquatic ecotoxicity impact scores from this stage are all relatively small and close to one another in magnitude (1.09, 1.40, and 1.40 kg aquatictox-equivalents/functional unit for BSA, SAC, and SABC, respectively). These scores represent between 3.7 and 4.7 percent of the totals. Of note is that SnPb has a greater impact score for the use/application stage than the lead-free alloys, but the SnPb use/application score only contributes 0.12 percent to SnPb total impacts. This is due to SnPb's high impact score at EOL. Impacts from the manufacturing stage are small, ranging from 0.013 to 0.16 kg aquatictox-equivalents/functional unit for SnPb and BSA, respectively. The manufacturing impacts for each alloy are less than 0.2 percent of total impacts and only 0.01 percent of SnPb impacts.

A benchmark of aquatic ecotoxicity impacts from burning a 60-watt lightbulb is provided here to help put the magnitude of the impacts into perspective. The difference between the SnPb and SAC ecotoxicity results is 1,234 kg aquatictox-equivalents/functional unit. The ecotoxicity impacts associated with burning a 60-watt bulb for one day is 2.48 kg aquatictox-equivalents and for one year is 905 kg aquatictox-equivalents; therefore, the difference between the SnPb and SAC results is equivalent to burning a 60-watt bulb for approximately 1 year and 4 months. On the other hand, the difference between the SAC and BSA results is only 13 kg aquatictox-equivalents/functional unit, which is equivalent to ecotoxicity impacts associated with burning a 60-watt bulb for about 5.2 days.

Aquatic Ecotoxicity Impacts by Process Group (Paste Solder)

Table 3-98 lists the aquatic ecotoxicity impacts of each of the process groups in the life-cycle of the solders. Within the EOL stage of the SnPb life-cycle, landfilling is the greatest contributor to total impacts (78 percent of total aquatic ecotoxicity impacts), followed by incineration (20 percent), and unregulated recycling/disposal (1.2 percent). Copper smelting and demanufacturing are small contributors to the total SnPb aquatic ecotoxicity impacts (0.0034 and 0.00001 percent, respectively).

When evaluating the lead-free alloys alone, unregulated recycling and disposal is the greatest process group contributor to EOL impacts, with scores of 15.0, 14.8, and 22.7 kg aquatictox-equivalents/functional unit for SAC, BSA, and SABC, respectively (which contribute 41 to 63 percent of the total life-cycle impacts depending on the alloy). The second greatest contributor to EOL impacts for the lead-free solders is landfilling (accounting for 3 to 5 percent of total impacts). For the lead-free alloys, unregulated recycling/disposal has far greater aquatic ecotoxicity impacts than landfilling, despite there being more electronics that are presumed to go to landfilling (72 percent) than unregulated disposal (4.5 percent). This is because only a small fraction of each metal in the lead-free alloys (between 0.000013 and 0.024 for all metals) was found to leach during the project's leachability testing (Chapter 2 and Appendix C), but some 12.5 percent (i.e., a fraction of 0.125) of solder metals sent to unregulated recycling and disposal are assumed to be released directly to surface waters via surface water runoff from waste electronics burn piles.

For the lead-free solders, the silver production process is the greatest contributor to upstream aquatic ecotoxicity impacts, contributing 24 to 51 percent to total impacts. For SAC, copper production is the next greatest contributor, followed by tin production, but these contributions are small (0.01 percent or less each). For BSA, after silver production, bismuth production is the next largest contributor at 1.82 percent, followed by tin production at 0.0016 percent contribution. The second greatest contributor for SABC also is bismuth production, however the score is only 0.00645 kg aquatictox-equivalents/functional unit, or 0.015 percent of the total aquatic ecotoxicity impacts. Tin and copper production contribute even less to total impacts (less than 0.008 percent).

The use/application stage has only one process group contributing to that life-cycle stage: solder reflow application; thus, no further discussion on the breakdown of this life-cycle stage is warranted. Although the manufacturing life-cycle stage contributes a small proportion to the overall impacts, Table 3-98 shows the contribution of the two process groups—solder manufacturing and post-industrial recycling—within the manufacturing stage. For all the alloys, post-industrial recycling has a greater aquatic ecotoxicity impact score than the solder manufacturing process group.

Table 3-98. Aquatic ecotoxicity impacts by life-cycle stage and process group (paste solder)

Life-cycle stage	**SnPb**		**SAC**		**BSA**		**SABC**	
Process group	Score*	%	Score*	%	Score*	%	Score*	%
UPSTREAM								
Sn production	5.06E-04	0.00004	7.41E-04	0.0020	3.79E-04	0.0016	7.48E-04	0.0019
Pb production	1.07E-01	0.0084	N/A	N/A	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	1.85E+01	50.9	5.53E+00	23.6	1.19E+01	31.0
Cu production	N/A	N/A	3.80E-03	0.0104	N/A	N/A	3.18E-03	0.0083
Bi production	N/A	N/A	N/A	N/A	4.26E-01	1.82	6.45E-03	0.0167
Total	**1.07E-01**	**0.0084**	**1.85E+01**	**50.9**	**5.96E+00**	**25.5**	**1.19E+01**	**31.0**
MANUFACTURING								
Solder manufacturing	1.13E-02	0.0009	1.40E-02	0.0386	1.12E-02	0.0480	1.41E-02	0.0366
Post-industrial recycling	1.49E-01	0.0117	4.48E-02	0.123	2.28E-02	0.0974	4.49E-02	0.117
Total	**1.61E-01**	**0.0126**	**5.88E-02**	**0.162**	**3.40E-02**	**0.145**	**5.90E-02**	**0.153**
USE/APPLICATION								
Reflow application	1.49E+00	0.117	1.40E+00	3.84	1.09E+00	4.68	1.40E+00	3.65
Total	**1.49E+00**	**0.117**	**1.40E+00**	**3.84**	**1.09E+00**	**4.68**	**1.40E+00**	**3.65**
END-OF-LIFE								
Landfill	9.99E+02	78.3	1.05E+00	2.89	1.19E+00	5.08	1.60E+00	4.16
Incineration	2.59E+02	20.3	2.75E-01	0.757	3.10E-01	1.33	6.47E-01	1.68
Demanufacturing	1.46E-04	0.00001	1.27E-04	0.0003	1.49E-04	0.0006	1.27E-04	0.0003
Cu smelting	4.33E-02	0.0034	5.03E-02	0.138	N/A	N/A	1.21E-01	0.315
Unregulated	1.54E+01	1.20	1.50E+01	41.3	1.48E+01	63.3	2.27E+01	59.0
Total	**1.27E+03**	**99.9**	**1.64E+01**	**45.1**	**1.63E+01**	**69.7**	**2.51E+01**	**65.2**
GRAND TOTAL	**1.27E+03**	**100**	**3.64E+01**	**100**	**2.34E+01**	**100**	**3.85E+01**	**100**

*The impact scores are in units of kilograms aquatictox-equivalents/1,000 cc of solder applied to a printed wiring board.
N/A=not applicable

Top Contributors to Aquatic Ecotoxicity Impacts (Paste Solder)

Table 3-99 presents the specific materials or flows contributing at least 1 percent of aquatic ecotoxicity impacts by solder. As expected from the results presented above, the SnPb impacts are dominated by the EOL stage. The aquatic ecotoxicity impacts are based on outputs to water. It is expected that the top contributors are lead emissions to water, mostly from landfilling, with a significant amount from incineration from leaching of incinerator ash disposed in landfills, and a smaller amount from unregulated recycling/disposal. Combined, lead emissions from these three processes constitute about 99.8 percent of the total life-cycle impacts. Lead emissions from landfilling alone are the largest contributor to SnPb impacts (78 percent). Further, lead emissions from landfilling are responsible for the fact that SnPb life-cycle impacts are far greater than those of the other alloys. This is partly a function of the higher leachability of lead, compared to the leachability of the other metals. For example, the fraction of lead in the SnPb alloy that was found to leach was approximately 0.19 (kg of Pb per kg of solder), compared to the fractions of 0.000019 and 0.000013 of silver and copper, respectively, in SAC (Chapter 2 and Appendix C).

Table 3-99. Top contributors to aquatic ecotoxicity impacts (paste solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	End-of-life	Solder landfilling (SnPb)	Lead emissions to water	78.3
	End-of-life	Solder incineration (SnPb)	Lead emissions to water	20.3
	End-of-life	Unregulated recycling and disposal (SnPb)	Lead emissions to water	1.20
SAC	Upstream	Silver production	Cadmium emissions to water	45.7
	End-of-life	Unregulated recycling and disposal (SAC)	Silver emissions to water	39.6
	Use/application	Electricity generation	Chlorine (dissolved) emissions to water	3.29
	End-of-life	Solder landfilling (SAC)	Silver emissions to water	2.42
	Upstream	Silver production	Lead emissions to water	2.13
	Upstream	Silver production	Zinc emissions to water	1.88
	End-of-life	Unregulated recycling and disposal (SAC)	Copper emissions to water	1.66
BSA	End-of-life	Unregulated recycling and disposal (BSA)	Silver emissions to water	63.3
	Upstream	Silver production	Cadmium emissions to water	21.2
	End-of-life	Solder landfilling (BSA)	Silver emissions to water	4.84
	Use/application	Electricity generation	Chlorine (dissolved) emissions to water	4.01
	End-of-life	Solder incineration (BSA)	Silver emissions to water	1.26
SABC	End-of-life	Unregulated recycling and disposal (SABC)	Silver emissions to water	32.8
	Upstream	Silver production	Cadmium emissions to water	27.8
	End-of-life	Unregulated recycling and disposal (SABC)	Copper emissions to water	26.2
	Use/application	Electricity generation	Chlorine (dissolved) emissions to water	3.13
	End-of-life	Solder landfilling (SACB)	Silver emissions to water	2.95
	Upstream	Silver production	Lead emissions to water	1.30
	End-of-life	Solder landfilling (SABC)	Copper emissions to water	1.21
	Upstream	Silver production	Zinc emissions to water	1.14
	End-of-life	Solder incineration (SABC)	Silver emissions to water	1.05

Another contributing factor leading to lead driving impacts, in addition to the leachability of lead, is that it has a relatively high aquatic toxicity measure (discussed below); however, lead does not have the highest relative aquatic toxicity compared to the other metals as it did for human health non-cancer toxicity.

Among the lead-free alloys, silver, cadmium, and copper emissions to water are the greatest contributors to aquatic ecotoxicity impacts. For SAC, cadmium emissions from silver production contribute 46 percent, and silver emissions from unregulated recycling and disposal contribute 40 percent. The remaining flows—chlorine emissions from reflow application, silver emissions from landfilling, lead and zinc emissions from silver production, and copper emissions from unregulated recycling and disposal—all contribute under 4 percent each to the total SAC ecotoxicity impacts.

For BSA, silver emissions from unregulated recycling and disposal contribute 63 percent, and cadmium emissions from silver production contribute nearly 20 percent to total aquatic ecotoxicity impacts. Silver emissions from landfilling, chlorine from electricity generation during reflow application, and silver emissions from incineration each contribute less than 5 percent.

The three top contributors to the SABC impacts are cadmium emissions from silver production (about 26 percent); and silver and copper emissions from unregulated recycling and disposal (27 percent each). The remaining top flows—chlorine from electricity generation for reflow application, silver and copper emissions from landfilling, lead and zinc emissions from silver production, and silver emissions from incineration—each contribute less than 4 percent to total impacts.

To help clarify the results, the aquatic ecotoxicity HVs for the top contributing flows are listed below in descending order of hazard (HVs for all materials classified as potentially toxic are presented in Appendix E):

- Cadmium: 28,500
- Silver: 10,050
- Copper: 2,732
- Lead: 976
- Zinc: 382
- Chlorine: 267

The HVs are relative values that rank the aquatic ecotoxicity potential of a chemical as compared to the average toxicity of many chemicals. The HVs are multiplied by the inventory output amounts for chemicals with potential aquatic ecotoxicity impacts to derive an impact score. Of the top contributors documented in Table 3-99, cadmium has the highest aquatic ecotoxicity HV, followed by silver. This helps explain why most impacts for the lead-free alternatives are driven by silver (from EOL processes) and cadmium (from silver production). For SnPb, on the other hand, the HV of lead is lower than cadmium and silver, however, the EOL output flows of silver and cadmium, both of which are a result of the presence of silver in the lead-free alloys, are not found in the SnPb inventory. Alternatively, the lead at EOL constitutes nearly all the impacts for SnPb, which are far greater than the total impacts for any of the other alloys.

3.2.13.3 Bar solder results

Total Aquatic Ecotoxicity Impacts by Life-Cycle Stage (Bar Solder)

Table 3-100 presents the bar solder results for aquatic ecotoxicity impacts by life-cycle stage, based on the impact assessment methodology presented above. The table lists the aquatic ecotoxicity impact scores per functional unit for the life-cycle stages of each bar solder alloy, as well as the percent contribution of each life-cycle stage to the total impacts. Figure 3-36 presents the results in a stacked bar chart.

Table 3-100. Aquatic ecotoxicity impacts by life-cycle stage (bar solder)

Life-cycle stage	**SnPb**		**SAC**		**SnCu**	
	Score*	%	Score*	%	Score*	%
Upstream	9.56E-02	0.0062	2.75E+01	13.9	7.03E-03	0.0808
Manufacturing	2.87E-01	0.0185	6.83E-02	0.0345	6.99E-02	0.804
Use/application	2.36E-01	0.0152	2.39E-01	0.120	2.39E-01	2.74
End-of-life	1.55E+03	99.96	1.70E+02	86.0	8.38E+00	96.4
Total	**1.55E+03**	**100**	**1.98E+02**	**100**	**8.70E+00**	**100**

*The impact scores are in units of kilograms of aquatictox-equivalents/1,000 cubic centimeters of solder applied to a printed wiring board.

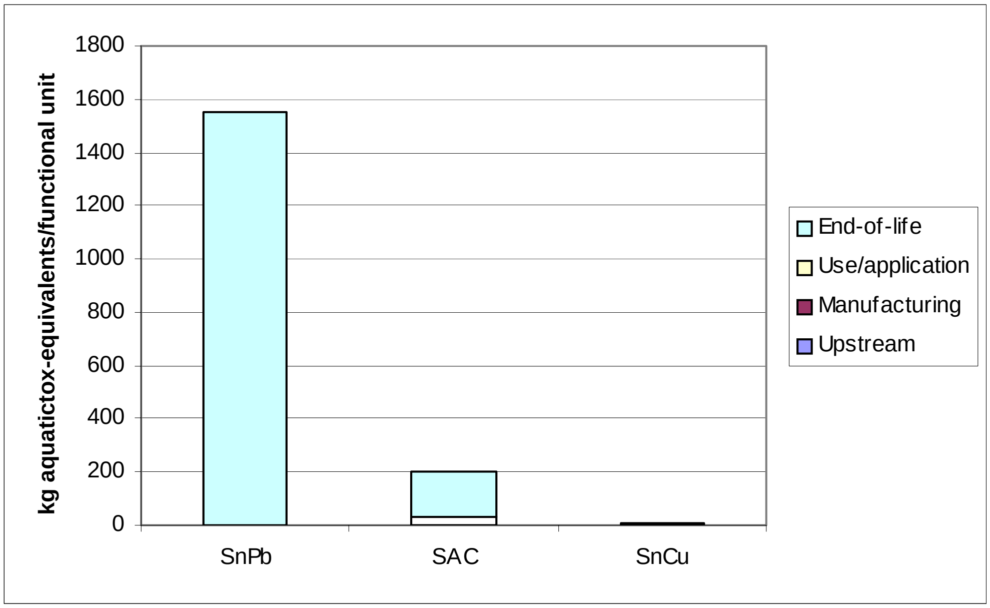

Figure 3-36. Bar Solder Total Life-Cycle Impacts: Aquatic Ecotoxicity

The total aquatic ecotoxicity impact score for SnPb (1,550 kg aquatictox-equivalents/functional unit) is far greater than the other bar solder alloys. SAC has the next greatest impact score (198 kg aquatictox-equivalents/functional unit), followed by SnCu with the lowest of 8.7 kg aquatictox-equivalents/functional unit.

The EOL stage accounts for nearly all of SnPb impacts, contributing 99.96 percent to the total aquatic ecotoxicity impact score. For the lead-free bar solder alternatives, the EOL stage is also the vast majority (96 and 86 percent), although the absolute scores are far lower than that of SnPb. For SAC, the upstream life-cycle stage contributes 14 percent to the total impacts.

The use/application stage is a small contributor to overall impacts for all three alloys, although it varies in terms of the percent contribution. Nonetheless, the aquatic ecotoxicity impact scores for all three alloys from this stage are all relatively small and close to one another in magnitude (0.236, 0.239, and 0.239 kg aquatictox-equivalents/functional unit for SnPb, SAC, and SnCu, respectively). Of note is that SnPb has a greater impact score for the use/application stage than the lead-free alloys, but the SnPb score only contributes 0.12 percent to SnPb total impacts. This is due to SnPb's high impact score at EOL. Impacts from the manufacturing stage are small, as are upstream impacts from SnPb and SnCu (all less than 0.3 kg aquatictox-equivalents/functional unit).

Aquatic Ecotoxicity Impacts by Process Group (Bar Solder)

Table 3-101 lists the aquatic ecotoxicity impacts of each of the process groups in the life-cycle of the bar solders. Within the EOL stage of the SnPb life-cycle, landfilling is the greatest contributor to total impacts (71 percent of total aquatic ecotoxicity impacts), followed by incineration (18 percent), and unregulated recycling/disposal (11 percent). Copper smelting and demanufacturing are small contributors to the total SnPb aquatic ecotoxicity impacts (0.0031 and 0.00001 percent, respectively).

When evaluating the lead-free alloys alone, unregulated recycling and disposal is the greatest process group contributor to EOL impacts, with scores of 169 and 7.89 kg aquatictox-equivalents/functional unit for SAC and SnCu, respectively (which contribute 85 and 91 percent of the total life-cycle impacts, respectively). The second greatest contributor to EOL impacts for the lead-free solders is landfilling (accounting for 0.6 or 4 percent of total impacts). For the lead-free alloys, unregulated recycling/disposal has far greater aquatic ecotoxicity impacts than landfilling, despite there being more electronics that are presumed to go to landfilling (72 percent) than unregulated disposal (4.5 percent). This is because only a small fraction of each metal in the lead-free bar alloys (between 0.000013 and 0.000027 for all metals) was found to leach during the project's leachability testing (Chapter 2 and Appendix C), but some 12.5 percent (i.e., a fraction of 0.125) of solder metals sent to unregulated recycling and disposal are assumed to be released directly to surface waters via surface water runoff from waste electronics burn piles.

Within the upstream life-cycle stage, silver production for SAC contributes nearly 14 percent while all the other metals production process groups are negligible contributors to the overall aquatic ecotoxicity impacts for all alloys. The use/application stage has only one process group contributing to that life-cycle stage: wave solder application. No further discussion on the breakdown of this life-cycle stage is warranted. Although the manufacturing life-cycle stage contributes a very small proportion to the overall impacts, Table 3-101 shows the contribution of the two process groups—solder manufacturing and post-industrial recycling—within the manufacturing stage. For all the alloys, post-industrial recycling has a greater aquatic ecotoxicity impact score than the solder manufacturing process group.

Table 3-101. Aquatic ecotoxicity impacts by life-cycle stage and process group (bar solder)

Life-cycle stage	**SnPb**		**SAC**		**SnCu**	
Process group	Score*	%	Score*	%	Score*	%
UPSTREAM						
Sn production	4.92E-04	0.00003	1.04E-03	0.0005	8.04E-04	0.0092
Pb production	9.51E-02	0.0061	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	2.75E+01	13.9	N/A	N/A
Cu production	N/A	N/A	6.35E-03	0.0032	6.23E-03	0.0716
Total	**9.56E-02**	**0.0062**	**2.75E+01**	**13.9**	**7.03E-03**	**0.0808**
MANUFACTURING						
Solder manufacturing	3.57E-02	0.0023	4.12E-02	0.0208	2.37E-02	0.272
Post-industrial recycling	2.51E-01	0.0162	2.71E-02	0.0137	4.63E-02	0.532
Total	**2.87E-01**	**0.0185**	**6.83E-02**	**0.0345**	**6.99E-02**	**0.804**
USE/APPLICATION						
Solder application	2.36E-01	0.0152	2.39E-01	0.1204	2.39E-01	2.7426
Total	**2.36E-01**	**0.015**	**2.39E-01**	**0.1204**	**2.39E-01**	**2.74**
END-OF-LIFE						
Landfill	1.11E+03	71.4	1.18E+00	0.597	3.91E-01	4.49
Incineration	2.73E+02	17.5	2.93E-01	0.148	9.70E-02	1.12
Demanufacture	1.63E-04	0.00001	1.42E-04	0.0001	1.41E-04	0.0016
Cu smelting	4.81E-02	0.0031	1.57E-03	0.0008	1.52E-03	0.0175
Unregulated	1.71E+02	11.0	1.69E+02	85.2	7.89E+00	90.7
Total	**1.55E+03**	**99.96**	**1.70E+02**	**86.0**	**8.38E+00**	**96.4**
GRAND TOTAL	**1.55E+03**	**100**	**1.98E+02**	**100**	**8.70E+00**	**100**

*The impact scores are in units of kg aquatictox-equivalents/1,000 cubic centimeters of solder applied to a printed wiring board.
N/A=not applicable

Top Contributors to Aquatic Ecotoxicity Impacts (Bar Solder)

Table 3-102 presents the specific materials or flows contributing at least 1 percent of aquatic ecotoxicity impacts by solder. As expected from the results presented above, the SnPb impacts are dominated by the EOL stage. The aquatic ecotoxicity impacts are based on outputs to water. It is expected that the top contributors are lead emissions to water, mostly from landfilling, with a significant amount from incineration (from leaching of incinerator ash disposed in landfills), and a smaller amount from unregulated recycling/disposal. Lead emissions from landfilling alone are the largest contributor to SnPb impacts (71 percent), further, lead emissions from landfilling are responsible for the fact that SnPb life-cycle impacts are far greater than those of the other alloys. This is partly a function of the higher leachability of lead compared to the leachability of the other metals. For example, the fraction of lead in the SnPb alloy that was found to leach was approximately 0.19 (kg of Pb per kg of solder), compared to the fractions of 0.000019 (kg of Pb per kg of solder) and 0.000013 (kg of Pb per kg of solder) of silver and copper, respectively, in SAC (Chapter 2 and Appendix C).

Table 3-102. Top contributors to aquatic ecotoxicity impacts (bar solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	End-of-life	Solder landfilling (SnPb)	Lead to water	71.4
	End-of-life	Solder incineration (SnPb)	Lead to water	17.6
	End-of-life	Unregulated recycling and disposal (SnPb)	Lead to water	11.0
SAC	End-of-life	Unregulated recycling and disposal (SAC)	Silver to water	81.8
	Upstream	Silver production	Cadmium to water	12.5
	End-of-life	Unregulated recycling and disposal (SAC)	Copper to water	3.42
SnCu	End-of-life	Unregulated recycling and disposal (SnCu)	Copper to water	90.4
	End-of-life	Solder landfilling (SnCu)	Copper to water	4.49
	Use/application	Electricity generation	Chlorine (dissolved) to water	2.35
	End-of-life	Solder incineration (SnCu)	Copper to water	1.12

Another contributing factor leading to lead driving impacts, in addition to the leachability of lead, is that it has a relatively high aquatic toxicity measure (discussed below). Lead does not have the highest relative aquatic toxicity compared to the other metals as it did for human health non-cancer toxicity.

Among the lead-free bar alloys, silver, cadmium, copper, and chlorine emissions to water are top contributors to aquatic ecotoxicity impacts. For SAC, silver emissions from unregulated recycling and disposal contribute about 82 percent, cadmium emissions from silver production contribute about 13 percent, and copper emissions from unregulated recycling and disposal contribute 3 percent.

For SnCu, copper from unregulated recycling and disposal contributes the greatest at 90 percent. Copper emissions from landfilling and incineration, as well as chlorine from wave application, each contribute less than 5 percent to the total aquatic ecotoxicity impact scores.

As described earlier in Section 3.2.13.2, the aquatic ecotoxicity HVs for the top contributing flows for the bar solders are listed below in descending order of hazard (HVs for all materials classified as potentially toxic are presented in Appendix E):

- Cadmium: 28,500
- Silver: 10,050
- Copper: 2,732
- Lead: 976
- Chlorine: 267

To reiterate from previous sections, the HVs are relative values that rank the aquatic ecotoxicity potential of a chemical as compared to the average toxicity of many chemicals. The HVs are multiplied by the inventory output amounts for chemicals with potential aquatic ecotoxicity impacts to derive an impact score. Of the top contributors documented in Table 3-102, cadmium has the highest aquatic ecotoxicity HV, followed by silver, and then copper. This helps explain why most impacts for SAC are driven by silver from EOL processes, cadmium from silver production, and copper from EOL processes. For SnCu, copper emissions from EOL processes dominate impacts, and for SnPb, lead emissions dominate impacts. The large impact score for SnPb also is a function of the higher leachability of lead, as discussed above.

3.2.13.4 Limitations and uncertainties

The LCIA methodology for aquatic ecotoxicity impacts is subject to the same structural or modeling limitations and toxicity data limitations discussed previously for the occupational and public health impact categories. For a detailed discussion, refer to the *Limitations and Uncertainties* subsection of Section 3.2.11.4. One important distinction is that more toxicity data tend to be available for aquatic effects than for human carcinogenic effects, for example. Of the 178 chemicals classified as potentially toxic in this LFSP LCA, 53 had outputs to water that should be considered in the aquatic ecotoxicity impact category. Of these, 41 had aquatic ecotoxicity data suitable for inclusion in the LCIA

The LCI data limitations also are similar to those described in preceding sections. For SnPb, EOL processes dominate total impacts. As a result, the limitations and uncertainties for SnPb are most influenced by the EOL limitations and uncertainties. Most of the SnPb impacts are from outputs to water from landfilling or incineration processes as derived from leachability testing associated with this project (see Appendix C). As primary data collected for the purposes of the LFSP, the leachability data are considered to be of relatively low uncertainty; however, further information about their limitations and uncertainties was presented in Section 3.2.12.4 and is applicable here.

The lead-free alloy results for both paste and bar solders, on the other hand, are more influenced by limitations and uncertainties in the unregulated recycling/disposal inventory. (Emissions from landfilling also are among the top contributors to lead-free impacts in some cases and, thus, are subject to the limitations and uncertainties described for lead outputs from landfilling.) Unregulated recycling/disposal uncertainties are greater than those associated with landfill outputs due to the almost complete absence of analytical data on the partitioning of metals among environmental media for unregulated recycling and disposal processes. Data from EPA trials currently underway to assess metal emissions from open burning of electronics waste could be used later to reassess the assumptions used in this LCA for unregulated recycling and disposal processes.

For the other EOL processes, there also are uncertainties associated with the inventory quantities as they were based on assumptions about partitioning of the metals to various media, depending on the EOL process. For incineration, secondary literature was reviewed to make assumptions about metal releases and partitioning to various environmental media. This introduced slightly more uncertainty into the incineration outputs than is expected with the landfilling data. Uncertainties from copper smelting and unregulated recycling/disposal have less effect on the results as they both contribute small proportions to total impacts. Nonetheless, uncertainties associated with copper smelting arise from the inability of the researchers to obtain direct quantitative data from primary data sources, as was discussed previously.

In addition to metal output uncertainties from landfilling and incineration, there are EOL uncertainties related to the assumptions about EOL dispositions to each EOL process (e.g., 72 percent of solder goes directly to landfilling for SnPb, SAC, SABC, and SnCu). These are discussed in greater detail in Chapter 2, limitations and uncertainties in the EOL inventory).

In addition to the EOL stage, the aquatic ecotoxicity impact scores of the silver-bearing alloys are largely influenced by the upstream life-cycle stage. Upstream uncertainties have been discussed in previous sections and relate to the fact that the data are from secondary data sources. Silver production, which accounts for large amounts of the total aquatic ecotoxicity impacts for most of the lead-free solders, has associated uncertainties that are described in Section 3.2.1.4. As presented in that section, although the secondary silver data set from GaBi is considered “good,” it is addressed with an alternate analyses in Section 3.3.

The use/application stage has a relatively small influence on the results. Nonetheless, the limitations and uncertainties related to electricity consumption and generation described previously apply here.

3.3 ALTERNATE ANALYSES

3.3.1 Reflow Application Energy Analysis

The energy requirements for the reflow application process are based on primary data collected from two facilities where test runs were conducted (described in Section 2.4). The two ovens in which these tests were performed represent different technologies resulting in a large range in energy consumption rates due to the difference in the efficiencies of the ovens. In the baseline analysis, an average energy consumption value from these two test runs was used in the determination of the life-cycle impacts reported earlier in Chapter 3. Table 3-103 shows the baseline energy consumption average and the low and high individual data points that were used to calculate the average. The low estimates are either 27 or 35 percent lower than the baseline and the high estimates are either 27 or 35 percent higher than the baseline.

Table 3-103. Energy estimates for the reflow application process

Alloy	Baseline energy*	Low energy*	Percent change from baseline	High energy*	Percent change from baseline
SnPb	115	73.9	-35	155	35
SAC	124	80.6	-35	168	35
BSA	82.4	60.1	-27	105	27
SABC	124	80.6	-35	168	35

* Units are in kWh/kg of solder applied to a printed wiring board. (*Note*: This unit is different from the impact results which are presented per unit *volume* of solder on a printed wiring board.)

For many of the impact categories evaluated, impacts from energy used in the use/application life-cycle stage constituted a majority of impacts. For paste solder, nearly all of the use/application energy consumption occurs during the reflow soldering process. Table 3-104 lists the impact categories, and the alloys within each category, for which a majority of the impacts resulted from the energy consumed during reflow. The only categories in which none of the alloys had a majority of their impacts from energy used during reflow application were occupational non-cancer, occupational cancer, public non-cancer, and aquatic ecotoxicity.

The analyses determine the sensitivity of the baseline impact results to the selection of a value for the energy used during reflow. To demonstrate the sensitivity, results of the baseline analysis were re-evaluated using the range of energy consumption values shown in Table 3-103 for the energy use impact category only. This category was selected as an example of the potential sensitivity because a large percentage (between about 81 and 92 percent) of the of the baseline impacts in this category for all four alloys resulted from the energy consumed during reflow.

Table 3-104. Impact categories and alloys with majority of impacts from energy used in reflow application of paste solders

Impact Category	**Alloy(s)**
Non-renewable resource use	SnPb, SAC, BSA, SABC
Renewable resource use	SnPb, SAC, BSA, SABC
Energy use	SnPb, SAC, BSA, SABC
Landfill space use	SnPb
Global warming	SnPb, SAC, BSA, SABC
Ozone depletion	SnPb, SAC, BSA, SABC
Photochemical smog	SnPb, BSA, SABC
Air acidification	SnPb, BSA, SABC
Air particulate matter	SnPb
Water eutrophication	SnPb, SAC, BSA, SABC
Water quality	SnPb, SAC, BSA, SABC
Public human health—cancer	SnPb, SAC, BSA, SABC

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. As shown in Figure 3-37, for all three scenarios (low energy, baseline, and high energy), SAC has the highest impacts, followed by SABC, SnPb, and finally BSA.

When considering the contributions of individual life-cycle stages to the energy use impact category (Section 3.2.2), the portion of the total life-cycle energy use impacts attributable to the energy use during the use/application stage remain substantial, even when the low energy data are used. This is illustrated in Table 3-105, which shows the percent contribution of the use/application stage for the low energy, the baseline average, and the high energy data. The table shows that even using the low energy values (i.e., a 27 to 35 percent decrease in energy use in reflow application depending on the alloy), the energy impact results remain driven by the use/application stage (73 to 88 percent) compared to the baseline where 82 to 91 percent of impacts are from the use/application stage.

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 as the energy use impact category and are unlikely to be as affected by a change in the reflow data. Overall, the analyses suggest 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 analysis represents a true or realistic range of the energy estimates for reflow applications process).

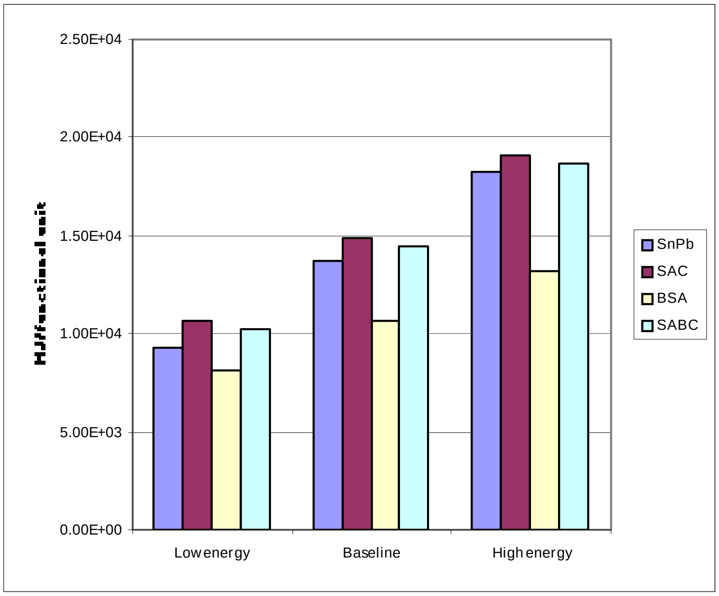

Figure 3-37. Sensitivity Analysis of Energy Consumption During Reflow Solder Application

Table 3-105. Use/application energy sensitivity analysis: percent contribution of use/application stage to energy impacts

Energy estimate	Percent Contribution			
	SnPb	SAC	BSA	SABC
Low energy	88.2	73.2	83.1	76.8
Baseline	91.2	78.9	85.8	82.0
High energy	94.0	85.1	89.5	87.4

3.3.2 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 SAC, six impact categories were dominated by the silver production process, including landfill space use, photochemical smog, air acidification, air particulates, public non-cancer, and aquatic ecotoxicity (presented in Table 3-120). For BSA, the landfill space use impact category had silver production as the top contributing process group; and for SABC, the landfill space use and the air particulate matter impact categories had silver production as the top contributing process group (see

Tables 3-121 and 3-122). As expected, SAC is more influenced by the silver production process group than the other alloys because of its greater silver content. In addition, the silver process contributed significantly to many other categories for each of the alloys, though it may not have been the dominant contributor.

Due to the large influence that silver production had on many of the impact categories, an alternate analysis to the baseline was performed by substituting an alternate silver data set (DEAM) for the GaBi silver mix data set used to calculate the baseline results. For a discussion of the GaBi data set and an explanation of why that data set was used for the baseline, please refer to Section 2.2. Tables 3-106 and 3-108 show the results of the alternate analyses for paste and bar solders respectively, as compared to the baseline. In the tables, bold entries indicate the highest impact score (i.e., the greatest environmental impacts) among the alloys within each impact category, while the shaded entries indicate the lowest impact score among alloys within each category.

The results of the alternate analysis are dramatic and can be readily observed in Table 3-123, which compares the baseline results for paste solders with those developed using the alternate DEAM silver data set. For the baseline analysis, SnPb had the highest impacts in six impact categories while SAC had the higher impacts in the remaining ten categories. Neither BSA nor SABC had impacts that were the highest impact score in any category; however, when results were generated using the DEAM data set, SnPb had the highest impacts in fourteen of the sixteen impact categories, with SAC (particulate matter) and BSA (NRR use) leading in one category each. In many cases, SAC was only slightly less than SnPb, and most likely within the error range of the data. Nonetheless, the analysis resulted in a noticeable change in relative results between SnPb and SAC. Likewise, SnPb had the lowest impact scores—indicating it was the best performer of the alloys evaluated—in five impact categories using the GaBi mixed silver data set, but did not register the lowest score in any impact category during the alternate analysis. BSA accounted for the lowest impact score in fifteen of the sixteen impact categories. These results indicate the high sensitivity of the overall life-cycle results for paste solders to the silver data set, and suggest that additional effort to further resolve the silver mining and extraction data would be well spent.

A comparison of the baseline and alternate analyses for bar solders is shown in Table 3-109. For the baseline analysis using the GaBi data set, SAC had highest life-cycle impacts in twelve impact categories while SnPb had highest impacts in the remaining four categories; however, results from the alternate analysis indicate that SAC had highest impacts in only seven impact categories and SnPb had highest impacts in nine impact categories. This is not as dramatic a change as was seen with the paste results; however, several impact-specific conclusions were altered. In addition, while SAC was not the lowest score for any impact categories in the baseline, it was the lowest in five impact categories in the alternate analysis. Again, this shows the importance of the silver inventory on results and the variability among different silver production data sets. The baseline is expected to be of good quality and is believed to be of greater quality than the DEAM data, but regardless of the relative quality of each data set, these results show the possible variability and sensitivity of the results to the silver inventory data.

Table 3-106. Alternative silver production analysis (paste solders)

Impact Category	Unit per functional unit*	Baseline				Alternate silver process			
		SnPb	**SAC**	**BSA**	**SABC**	**SnPb**	**SAC**	**BSA**	**SABC**
NRR use	kg	1.61E+03	**1.82E+03**	1.76E+03	1.72E+03	1.61E+03	1.52E+03	**1.67E+03**	1.53E+03
RR use	kg	**3.48E+04**	3.47E+04	2.64E+04	3.41E+04	**3.48E+04**	3.26E+04	2.58E+04	3.28E+04
Energy use	MJ	1.25E+04	**1.36E+04**	9.76E+03	1.31E+04	**1.25E+04**	1.24E+04	9.40E+03	1.24E+04
Landfill	m^3	2.75E-03	**1.62E-02**	6.57E-03	1.13E-02	**2.75E-03**	2.62E-03	2.53E-03	2.63E-03
Global warming	kg CO_2-Equiv.	8.17E+02	**8.73E+02**	6.31E+02	8.49E+02	**8.17E+02**	8.15E+02	6.14E+02	8.11E+02
Ozone depletion	kg CFC-11-equiv.	9.95E-05	**1.10E-04**	7.98E-05	1.04E-04	**9.95E-05**	9.35E-05	7.49E-05	9.39E-05
Photochemical smog	kg ethene-equiv.	3.13E-01	**6.18E-01**	3.61E-01	5.05E-01	**3.13E-01**	3.00E-01	2.66E-01	3.01E-01
Acidification	kg SO_2-equiv.	6.50E+00	**1.25E+01**	7.32E+00	1.03E+01	**6.50E+00**	6.30E+00	5.48E+00	6.30E+00
Particulate matter	kg	4.52E-01	**1.30E+00**	5.85E-01	1.01E+00	4.52E-01	**4.95E-01**	3.44E-01	4.88E-01
Eutrophication	kg phosphate-equiv.	**1.22E-01**	1.18E-01	9.06E-02	1.17E-01	**1.22E-01**	1.14E-01	8.95E-02	1.15E-01
Water quality	kg	1.79E-01	**2.26E-01**	1.64E-01	2.06E-01	**1.79E-01**	1.68E-01	1.47E-01	1.69E-01
Occupational non-cancer	kg noncancertox-equiv.	**5.60E+05**	8.12E+03	2.34E+03	5.25E+03	**5.60E+05**	1.02E+04	2.95E+03	6.57E+03
Occupational cancer	kg cancertox-equiv.	**7.74E+01**	7.41E+01	6.11E+01	7.58E+01	**7.74E+01**	7.30E+01	6.71E+01	7.30E+01
Public non-cancer	kg noncancertox-equiv.	**8.80E+04**	1.05E+04	5.01E+03	7.84E+03	**8.80E+04**	2.99E+03	2.76E+03	2.99E+03
Public cancer	kg cancertox-equiv.	6.96E+00	**7.05E+00**	5.15E+00	6.51E+00	**6.96E+00**	5.44E+00	4.67E+00	5.45E+00
Aquatic ecotoxicity	kg aquatictox-equiv.	**1.27E+03**	3.64E+01	2.34E+01	3.85E+01	**1.27E+03**	1.79E+01	1.79E+01	2.66E+01

*The functional unit is 1,000 cc of solder applied to a printed wiring board.

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 3-107. Comparison of baseline and alternate LCA analysis (paste solders)

Solder Alloy	Baseline		Alternate	
	High	Low	High	Low
SnPb	6	5	14	0
SAC	10	0	1	1
BSA	0	11	1	15
SABC	0	0	0	0

Table 3-108. Alternative silver production analysis (bar solders)

Impact Category	unit per functional unit*	Baseline			Alternate silver process		
		SnPb	SAC	SnCu	SnPb	SAC	SnCu
NRR use	kg	3.15E+02	**7.68E+02**	3.12E+02	3.15E+02	**3.29E+02**	3.12E+02
RR use	kg	6.03E+03	**8.76E+03**	5.83E+03	**6.03E+03**	5.75E+03	5.83E+03
Energy use	MJ	2.91E+03	**5.77E+03**	3.40E+03	2.91E+03	**4.04E+03**	3.32E+03
Landfill	m^3	1.34E-03	**2.14E-02**	1.33E-03	**1.34E-03**	1.31E-03	1.33E-03
Global warming	kg CO_2-Equiv.	1.87E+02	**3.57E+02**	2.16E+02	1.87E+02	**2.71E+02**	2.16E+02
Ozone depletion	kg CFC-11-equiv.	1.87E-05	**4.13E-05**	1.78E-05	**1.87E-05**	1.71E-05	1.78E-05
Photochemical smog	kg ethene-equiv.	6.98E-02	**5.51E-01**	7.06E-02	6.98E-02	**7.88E-02**	7.06E-02
Acidification	kg SO_2-equiv.	1.43E+00	**1.10E+01**	1.53E+00	1.43E+00	**1.81E+00**	1.53E+00
Particulate matter	kg	1.49E-01	**1.47E+00**	1.99E-01	1.49E-01	**2.78E-01**	1.99E-01
Eutrophication	kg phosphate-equiv.	2.14E-02	**2.57E-02**	2.06E-02	**2.14E-02**	2.02E-02	2.06E-02
Water quality	kg	3.98E-02	**1.20E-01**	3.64E-02	**3.98E-02**	3.37E-02	3.64E-02
Occ non-cancer	kg noncancertox-equiv.	**7.15E+05**	1.09E+04	6.53E+01	**7.15E+05**	1.39E+04	6.53E+01
Occ cancer	kg cancertox-equiv.	**5.94E+01**	5.75E+01	5.49E+01	**5.94E+01**	5.90E+01	5.49E+01
Public non-cancer	kg noncancertox-equiv.	**1.34E+05**	1.22E+04	7.33E+02	**1.34E+05**	1.01E+03	7.33E+02
Public cancer	kg cancertox-equiv.	6.87E+00	**1.24E+01**	9.96E+00	6.87E+00	**1.01E+02**	9.96E+00
Aquatic toxicity	kg aquatictox-equiv.	**1.55E+03**	1.98E+02	8.70E+00	**1.55E+03**	1.71E+02	8.70E+00

*The functional unit is 1,000 cc of solder applied to a printed wiring board.

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 3-109. Comparison of baseline and alternate LCA analysis (bar solders)

Solder Alloy	Baseline		Alternate	
	High	Low	High	Low
SnPb	4	6	9	6
SAC	12	0	7	5
SnCu	0	10	0	5

3.3.3 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). Two major contributors to these high SnPb results were the high leachability of lead and the fact that the lead has a very high relative toxicity. The TCLP leachability study conducted to determine the landfilling outputs is based on standard EPA TCLP test protocol using acetic acid, a substance known to readily leach lead. It is unknown to what extent these test conditions represent actual landfill conditions, which can vary dramatically over the lifetime of a landfill. It should be noted that only two impact categories (public non-cancer and aquatic ecotoxicity) were largely influenced by the EOL landfilling process, with the SnPb alloy particularly affected in both cases. To determine the sensitivity of the results to the lead leachability data, this section presents the results of an alternate analysis using the detection limit of lead as a lower bound of possible lead leachability during the TCLP study.

For the alternate analysis, the measured fraction of lead detected in the leachate during leachability testing of 0.19 (the baseline analysis) was replaced with the fraction of 0.000021 based on the TCLP detection limit for lead (0.01 Pb). The life-cycle impacts for both the public non-cancer and the aquatic ecotoxicity categories were then recalculated.

Tables 3-110 and 3-111 present the paste and bar results, respectively, for both the baseline analysis and the alternate lead leachate analysis. As shown in the tables, even with the assumption that lead essentially does not leach (i.e., assuming the study detection limit for the leachability of lead), the SnPb alloy impacts 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; however, the relative differences between SnPb and the lead-free alloys are far less than in the baseline analysis.

Table 3-110. Alternative lead leachate analysis for selected impact categories in the paste solder results

Impact category	Unit per functional unit (b)	Baseline				Alternate lead leachate data			
		SnPb	SAC	BSA	SABC	SnPb	SAC	BSA	SABC
Public non-cancer	kg noncancertox-equiv.	**8.80E+04**	1.05E+04	5.01E+03	7.84E+03	**2.41E+04**	1.05e+04	5.01E+03	7.84E+03
Aquatic ecotoxicity	kg aquatictox-equiv.	**1.27E+03**	3.64E+01	2.34E+01	3.85E+01	**2.76E+02**	3.64E+01	2.34E+01	3.85E+01

(a) Impact categories selected are those that were highly impacted by the leachate data in the baseline analysis.

(b) The functional unit is 1,000 cc of solder on a printed wiring board.

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 3-111. Alternative lead leachate analysis for selected impact categories in the bar solder results

Impact category	Unit per functional unit (b)	Baseline			Alternate lead leachate data		
		SnPb	**SAC**	**SnCu**	**SnPb**	**SAC**	**SnCu**
Public non-cancer	kg noncancertox-equiv.	**1.33E+05**	1.22E+04	7.26E+02	**6.23E+04**	1.22E+04	7.26E+02
Aquatic ecotoxicity	kg aquatictox-equiv.	**1.55E+03**	1.98E+02	8.70E+00	**4.44E+02**	1.98E+02	8.69E+00

(a) Impact categories selected are those that were highly impacted by the leachate data in the baseline analysis.

(b) The functional unit is 1,000 cc of solder on a printed wiring board.

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.

These results are not completely unexpected given the high toxicity of lead compared to the other metals. 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.

3.4 SUMMARY OF LIFE-CYCLE IMPACT ANALYSIS CHARACTERIZATION AND RESULTS

This section presents an overview of the characterization methods and the life-cycle impact results for the paste and bar solder alloys. Section 3.4.1 provides the equations for each impact category that are used to calculate impact scores. Section 3.4.2 describes the LCIA data sources and data quality. For both paste and bar solders, respectively, Sections 3.4.3 and 3.4.4 provide the total life-cycle impact category indicator scores for each alloy for each of the sixteen impact categories evaluated in this study.

The LFSP LCIA methodology does not perform the optional LCIA steps of normalization (calculating the magnitude of category indicator results relative to a reference value), grouping (scoring and possibly ranking of indicators across categories), or weighting (converting indicator results based on importance and possibly aggregating them across impact categories). Grouping and weighting, in particular, are subjective steps that depend on the values of different individuals, organizations, or societies performing the analysis. Since the LFSP involves a variety of stakeholders from different geographic regions and with different values, these more subjective steps were intentionally excluded from the LFSP LCIA methodology. Normalization also was intentionally not included as there are not universally accepted normalization reference values for all the impact categories included in this study. Furthermore, one of the primary purposes of this research is to identify the relative differences in the potential impacts among alloys, and normalization within impact categories would not affect the relative differences among alloys within the impact categories.

Section 3.4.5 summarizes the limitations and uncertainties associated with the LCIA methodology as well as the general limitations and uncertainties associated with the results.

3.4.1 Impact Score Equations

Table 3-112 summarizes the impact categories, associated impact score equations, and the input or output data required for calculating natural resource impacts. Each of these characterization equations are loading estimates. For a more detailed discussion of loading estimates, refer to Section 3.1.

Table 3-112. Summary of natural resources impact scoring

Impact category	Impact score approach	Data required from inventory (per functional unit)	
		Inputs	**Outputs**
Use of renewable resources	$IS_{RR} = Amt_{RR} x (1 - RC)$	Material mass (kg) (e.g., water)	None
Use/depletion of non-renewable resources	$IS_{NRR} = Amt_{NRR} x (1 - RC)$	Material mass (kg)	None
Energy use, general energy consumption	$IS_E = Amt_E$ or $(Amt_F x H/D)$	Energy (MJ) (electricity, fuel)	None
Landfill space use	$IS_L = Amt_W / D$	None	Mass of waste (hazardous and solid waste combined) (kg) and density (e.g., volume, m^3)

Abbreviations: RC=recycled content; H=heat value of fuel *i*; D=density of fuel *i*.

The term abiotic ecosystem refers to the nonliving environment that supports living systems. Table 3-113 presents the impact categories, impact score equations, and inventory data requirements for abiotic environmental impacts to atmospheric resources.

Table 3-113. Summary of atmospheric resource impact scoring

Impact category	Impact score approach	Data required from inventory (per functional unit)	
		Inputs	**Outputs**
Global warming	$IS_{GW} = EF_{GWP} x Amt_{GG}$	None	Amount of each greenhouse gas chemical released to air
Stratospheric ozone depletion	$IS_{OD} = EF_{ODP} x Amt_{ODC}$	None	Amount of each ozone depleting chemical released to air
Photochemical smog	$IS_{POCP} =EF_{POCP} x Amt_{POC}$	None	Amount of each smog-creating chemical released to air
Acidification	$IS_{AP} = EF_{AP} x Amt_{AC}$	None	Amount of each acidification chemical released to air
Air quality (particulate matter)	$IS_{PM} = Amt_{PM}$	None	Amount of particulates: PM_{10} or TSP released to air [a]

[a] Assumes PM_{10} and TSP are equal; however, using TSP will overestimate PM_{10}.

Table 3-114 presents the impact categories, impact score equations, and required inventory data for abiotic environmental impacts to water resources.

Table 3-114. Summary of water resource impact scoring

Impact category	Impact score approach	Data required from inventory (per functional unit)	
		Inputs	Outputs
Water eutrophication	$IS_{EUTR} = EF_{EP} \text{ x } Amt_{EC}$	None	Amount of each eutrophication chemical released to water
Water quality (BOD and TSS)	$IS_{WQ} = Amt_{BOD} + Amt_{BOD}$	None	Amount of BOD and suspended solids (TSS) in each wastewater stream released to surface water
Water quality (TSS)	$IS_{TSS} = Amt_{TSS}$	None	Amount of suspended solids (TSS) in each wastewater stream released to surface water

Table 3-115 summarizes the human health and ecotoxicity impact scoring approaches. The impact categories, impact score equations, the type of inventory data, and the chemical properties required to calculate impact scores are presented. The human health effects and ecotoxicity impact scores are based on the scoring of inherent properties approach to characterization. For a more detailed discussion of characterization methods, refer to Section 3.1.

Table 3-115. Summary of human health and ecotoxicity impact scoring

Impact category	Impact score equations	Data required from inventory (per functional unit)		Chemical properties data required
		Inputs	Outputs	
Chronic human health effects—occupational, cancer	$IS_{CHO\text{-}CA} = HV_{CA} \text{ x } Amt_{TCinput}$	Mass of each primary and ancillary toxic chemical	None	WOE or SF
Chronic human health effects—occupational, noncancer	$IS_{CHO\text{-}NC} = HV_{NC} \text{ x } Amt_{TCinput}$	Mass of each primary and ancillary toxic chemical	None	Mammal NOAEL or LOAEL
Chronic human health effects—public, cancer	$IS_{CHP\text{-}CA} = HV_{CA} \text{ x } Amt_{TCoutput}$	None	Mass of each toxic chemical released to air and surface water	WOE or SF
Chronic human health effects—public, noncancer	$IS_{CHP\text{-}NC} = HV_{NC} \text{ x } Amt_{TCoutput}$	None	Mass of each toxic chemical released to air and surface water	Mammal NOAEL or LOAEL
Aquatic ecotoxicity	$IS_{AQ} = (HV_{FA} + HV_{FC}) \text{ x } Amt_{TCoutput,water}$	None	Mass of each toxic chemical released to surface water	Fish LC_{50} and/or fish NOEL

Individual impact scores are calculated for inventory items for a certain impact category and can be aggregated by inventory item (e.g., a certain chemical), process, life-cycle stage, or entire product profile. For example, global warming impacts can be calculated for one inventory item (e.g., CO_2 releases), for one process that could include contributions from several inventory items (e.g., electricity generation), for a life-cycle stage that may consist of several process steps (e.g., product manufacturing), or for an entire profile (e.g., a functional unit of a solder).

3.4.2 LCIA Data Sources and Data Quality

Data that are used to calculate impacts come from: (1) equivalency factors or other parameters used to identify hazard values; and (2) LCI items. Equivalency factors and data used to develop hazard values presented in this methodology include GWP, ODP, POCP, AP, EP, WOE, SF, mammalian LOAEL/NOAEL, fish LC_{50}, and fish NOEL. Published lists of the chemical-specific parameter values exist for GWP, ODP, POCP, AP, and EP (see Appendix D). The other parameters may exist for a large number of chemicals, and several data sources must be searched to identify the appropriate parameter values. Priority is given to peer-reviewed databases (e.g., Health Effects Assessment Summary Tables [HEAST], Integrated Risk Information System [IRIS], Hazardous Substances Data Bank [HSDB]), next other databases (e.g., Registry of Toxic Effects of Chemical Substances [RTECS]), then other studies or literature, and finally estimation methods (e.g., structure-activity relationships [SARs] or quantitative structure-activity relationships [QSARs]). The specific toxicity data that are used in the LFSP are presented in Appendix E.

The sources of each parameter presented in this report and the basis for their values are presented in Table 3-116. Data quality is affected by the data source itself, the type of data source (e.g., primary versus secondary data), the currency of the data, and the accuracy and precision of the data. The sources and quality of the LCI data used to calculate impact scores were discussed in Chapter 2. Data sources and data quality for each impact category are discussed further in Section 3.2, LCIA Results.

Table 3-116. Data sources for equivalency factors and hazard values

Parameter	Basis of parameter values	Source
Global warming potential	Atmospheric lifetimes and radiative forcing compared to CO_2	IPCC, 2001
Ozone depletion potential	The change in the ozone column in the equilibrium state of a substance compared to CFC-11	UNEP, 2003; WMO 1999
Photochemical oxidant creation potential	Simulated trajectories of ozone production with and without VOCs present compared to ethene	Heijungs *et al.*, 1992; EI, 1999
Acidification potential	Number of hydrogen ions that can theoretically be formed per mass unit of the pollutant being released compared to SO_2	Heijungs *et al.*, 1992; Hauschild and Wenzel, 1997
Nutrient enrichment/eutrophication potential	Ratio of N to P in the average composition of algae ($C_{106}H_{263}O_{110}N_{16}P$) compared to phosphate (PO_4^{3-})	Heijungs *et al.*, 1992; Lindfors *et al.*, 1995

Table 3-116. Data sources for equivalency factors and hazard values

Parameter	Basis of parameter values	Source
Weight-of-evidence	Classification of carcinogenicity by EPA or IARC based on human and/or animal toxicity data	EPA, 1999; IARC, 1998
Slope factor	Measure of an individual's excess risk or increased likelihood of developing cancer if exposed to a chemical, based on dose-response data	IRIS and HEAST as cited in RAIS online database
Mammalian: LOAEL/NOAEL	Mammalian (primarily rodent) toxicity studies	IRIS, HEAST and various literature sources provided by EPA and/or UT contractor
Fish lethal concentration to 50 percent of the exposed population (LC_{50})	Fish (primarily fathead minnow) toxicity studies	Various literature sources and Ecotox database
Fish NOEL	Fish (primarily fathead minnow) toxicity studies	Literature sources and Ecotox database

3.4.3 Paste Solder Results Summary

The indicator results presented throughout the remainder of this section are the result of the characterization step of the LCIA methodology where LCI results are converted to common units and aggregated within an impact category. Results are expressed in units specific to an individual impact category and, therefore, cannot be summed or compared across impact categories.

Table 3-117 presents a summary of the paste solder results for each impact category calculated using the impact assessment methodology presented in previous subsections of Section 3.2. Impact scores shown in bold indicate the alloy with the highest impact score in an impact category, while shaded scores indicate the alloy with the lowest impact score. SnPb has the greatest impact category indicator in six impact categories, including eutrophication, RR use, and four toxicity-related categories—public non-cancer, occupational non-cancer, occupational cancer, and aquatic ecotoxicity. SAC has the highest impact category indicator in the remaining ten impact categories: NRR use, energy use, landfill space use, global warming, ozone depletion, photochemical smog, acidification, particulate matter, water quality, and public cancer. SnPb has the lowest impact category indicator among the alloys in five impact categories: NRR use, landfill space use, photochemical smog, acidification, and particulate matter. BSA has the lowest indicators in the remaining eleven categories.

When evaluating the lead-free alternatives alone, without considering SnPb, BSA has the lowest life-cycle impact score in all categories and SAC has the highest in all categories, except aquatic ecotoxicity and occupational cancer, for which SABC has the highest impact scores. Both impacts scores, however, are not much greater than those for SAC, and all the lead-free alloys have substantially lower aquatic ecotoxicity impacts than SnPb. These scores only indicate the relative or incremental differences among the alloys and do not necessarily indicate any level of concern. The LCIA is not intended to quantify the significance of any particular impact score, but instead it shows the relative difference among the alloys within a particular impact category; however, for some impact categories, especially the toxicity categories, results are not necessarily linear. In other words, a score of ten does not mean potential impacts are ten times worse than a score of one. Detailed discussions of the results of each impact category, along with the associated uncertainties, are presented in Section 3.2.2.

Table 3-117. 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 3-118 summarizes the top contributing life-cycle stages for each alloy by impact category. The life-cycle stage or stages that contribute fifty percent or more to impacts in each impact category are listed in the table. In cases where an individual life-cycle stage did not constitute a majority, the top stages that together exceed fifty percent are listed. In these cases, the life-cycle stage listed first represents the one with a greater percentage of impacts attributable to that impact category.

As shown in the table, the use/application life-cycle stage dominates much of the impacts. For SnPb, thirteen out of sixteen impact categories have the majority of their impacts from the use/application stage. The manufacturing stage dominates in one category: occupational non-cancer, although it is not a majority by itself. The EOL stage is a top contributor to occupational non-cancer and a majority for two other toxicity-related impact categories, public non-cancer and aquatic ecotoxicity. The EOL impacts affected by outputs are based on the metal constituents of the solders and not other materials in a PWB or the product which houses the PWB; that is, outputs from incineration include only the solder metals and not combustion products of the PWB itself. An analysis of an entire PWB assembly would likely result in differing impacts than shown in this analysis.

Table 3-118. Solder paste life-cycle stages contributing a majority of impacts

Impact category	SnPb	SAC	BSA	SABC
Non-renewable resource use	Use/application	Use/application	Use/application	Use/application
Renewable resource use	Use/application	Use/application	Use/application	Use/application
Energy use	Use/application	Use/application	Use/application	Use/application
Landfill space use	Use/application	Upstream	Upstream	Upstream
Global warming	Use/application	Use/application	Use/application	Use/application
Ozone depletion	Use/application	Use/application	Use/application	Use/application
Photochemical smog	Use/application	Upstream	Use/application	Use/application
Air acidification	Use/application	Upstream	Use/application	Use/application
Air particulates	Use/application	Upstream	Upstream	Upstream
Water eutrophication	Use/application	Use/application	Use/application	Use/application
Water quality	Use/application	Use/application	Use/application	Use/application
Occupational health—non-cancer	Manufacturing, End-of-life	Manufacturing, End-of-life	End-of-life, Use/application	Manufacturing, End-of-life
Occupational health—cancer	Use/application	Use/application	Use/application	Use/application
Public human health—non-cancer	End-of-life	Upstream	Upstream	Upstream
Public human health—cancer	Use/application	Use/application	Use/application	Use/application
Aquatic ecotoxicity	End-of-life	Upstream	End-of-life	End-of-life

For the lead-free alternatives, the upstream life-cycle stage plays a more important role than it does for SnPb. SAC has nine impact categories where the use/application stage is the majority contributor and six categories in which the upstream stage provides the majority of impacts. Manufacturing and EOL are top contributors to only one impact category: occupational non-cancer. The BSA impacts are driven by the use/application stage in eleven categories, the upstream stage in three categories, and the EOL in two categories. Manufacturing, along with EOL, contributes to the majority of impacts in the occupational non-cancer impact category. The impact categories for SABC are driven by the same stages as BSA, with the exception of the occupational non-cancer impact category. SABC occupational non-cancer impacts are driven by the manufacturing and EOL stages, as is the case for SnPb and SAC.

For all categories that are dominated by the use/application stage, except occupational non-cancer, impacts are from the electricity generation for the reflow application process. For occupational non-cancer, the use/application stage dominates from the actual reflow application process. In most cases where the upstream stage dominates impacts in a category, it is silver production that is responsible for the high impacts, as is illustrated in the tables that follow. In the manufacturing stage, which contributes significantly to occupational non-cancer for SnPb, SAC, and SABC, it is the solder manufacturing process that is the source.

As stated in the previous sections, because the use/application stage is so dominant, a sensitivity analysis of the use/application energy is provided in Section 3.3. Additionally, alternative analyses are conducted with (1) alternative silver production process data, and (2) the results of the less aggressive leachability study for EOL processes. These are also presented in Section 3.3.

Table 3-119 through 3-122 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 for each alloy nearly all impact categories are driven by a different flow. For example, in the SnPb life-cycle, hard coal is the top contributor to energy impacts, sulphur dioxide is the top contributor to photochemical smog, and COD is the top contributor to water eutrophication (e.g., nutrient enrichment).

There are some flows that are top contributors to more than one impact category. For example, sulphur dioxide that drives photochemical smog and air acidification in the SnPb life-cycle is from electricity generation associated with reflow application. In the lead-free solder life-cycles, sulphur dioxide is the top contributor to three categories: photochemical smog, air acidification, and public human health (non-cancer); however, in these cases, the sulphur dioxide is from silver production in the upstream life-cycle stage, as opposed to electricity generation for reflow application in the case of SnPb.

Another top flow in the SnPb life-cycle that contributes to more than one category is lead emissions to water from landfilling. This is essentially the leachate from landfilling the SnPb alloy. Lead emissions to water contribute 72.6 percent to the public health (non-cancer) impact category and 78.3 percent to the aquatic ecotoxicity impact category.

In several instances, the top contributing individual flows comprise a large majority of the total contribution to the alloy’s life-cycle impacts within a category. For example, COD constitutes 97.1 percent of the total water eutrophication impacts. As there are not a large amount of chemicals for which there are eutrophication potentials, and the inventory in this project only has a few water eutrophying chemicals, it is understandable that one material might greatly dominate impacts. This is true for COD, despite its relatively low eutrophication potential (see Appendix D).

Many top contributors constitute a majority of the total 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. For each alloy, however, they were not always the same impact categories that contribute greater than fifty percent. For example, with aquatic ecotoxicity, silver emissions to water from unregulated recycling/disposal of BSA (Table 3-121) contribute sixty-three percent, while cadmium emissions to water from silver production for SAC (Table 3-120) are only forty-six percent of total aquatic ecotoxicity impacts.

Table 3-119. 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	SnPb 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 3-120. 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 3-121. 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 3-122. 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

3.4.4 Bar Solder Results Summary

Table 3-123 presents a summary of the bar solder results for each impact category calculated using the impact assessment methodology presented in previous subsections of Section 3.2. Impact scores shown in bold indicate the alloy with the highest impact score in an impact category, while shaded scores indicate the alloy with the lowest impact score. SnPb has the greatest impact category indicator in four impact categories, all of which are toxicity-related categories—public non-cancer, occupational non-cancer, occupational cancer, and aquatic ecotoxicity. SAC has the highest impact category indicator in the remaining twelve impact categories. SnPb has the lowest impact category indicator among the alloys in five impact categories: energy use, global warming, photochemical smog, acidification, and particulate matter. BSA has the lowest indicators in the remaining eleven categories.

When evaluating the lead-free alternatives alone, without considering SnPb, SAC has the highest impact score in all sixteen of the categories evaluated. Conversely, SnCu had the lowest indicator scores. These scores only indicate the relative or incremental differences among the alloys and do not necessarily indicate any level of concern. The LCIA is not intended to quantify the significance of any particular impact score, but instead it shows the relative difference among the alloys within a particular impact category. Detailed discussions of the results of each impact category, along with the associated uncertainties, are presented in Section 3.2.2.

Table 3-123. 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.

Table 3-124 summarizes the top contributing life-cycle stages for each alloy by impact category. The life-cycle stage or stages that contribute fifty percent or more to impacts in each impact category are listed in the table. In cases where an individual life-cycle stage did not constitute a majority, the top stages that together exceed fifty percent are listed. In these cases, the life-cycle stage listed first represents the one with a greater percentage of impacts attributable to that impact category.

Table 3-124. Bar solder life-cycle stages contributing a majority of impacts

Impact category	**SnPb**	**SAC**	**SnCu**
Non-renewable resource use	Use/application	Upstream	Use/application
Renewable resource use	Use/application	Use/application	Use/application
Energy use	Use/application	Upstream	Use/application
Landfill space use	End-of-life	Upstream	End-of-life
Global warming	Use/application	Upstream	Use/application
Ozone depletion	Use/application	Upstream	Use/application
Photochemical smog	Use/application	Upstream	Use/application
Air acidification	Use/application	Upstream	Use/application
Air particulates	Upstream	Upstream	Upstream
Water eutrophication	Use/application	Use/application	Use/application
Water quality	Use/application	Upstream	Use/application
Occupational health—non-cancer	End-of-life, Manufacturing	End-of-life, Manufacturing	Use/application, Manufacturing
Occupational health—cancer	Use/application, Manufacturing	Use/applications, Upstream	Use/application, Manufacturing
Public human health—non-cancer	End-of-life	Upstream	Use/application
Public human health—cancer	Use/application	Use/application	Use/application
Aquatic ecotoxicity	End-of-life	End-of-life	End-of-life

As shown in the table, the use/application life-cycle stage dominates the impacts. For SnPb, eleven of the sixteen impact categories are driven by contributions from the use/application stage, with end-of-life processes dominating four other impact categories. Similarly, the use/application stage is the major contributor to thirteen of the impact categories for the SnCu alloy. Upstream and end-of-life processes contribute the majority of the impacts in the remaining SnCu impact categories. The manufacturing stage dominates in one category: occupational non-cancer, although it is not a majority by itself. The EOL impacts affected by outputs are based on the metal constituents of the solders and not other materials in a PWB or the product which houses the PWB; that is, outputs from incineration include only the solder metals and not combustion products of the PWB itself. An analysis of an entire PWB assembly would likely result in differing impacts than shown in this analysis.

For the lead-free solder alternative, SAC, the upstream life-cycle stage plays a more important role than it does for SnPb. SAC has ten impact categories where the upstream stage is the majority contributor, while the use/applications stage dominates another four categories. Like the other two solders, the end-of-life stage drives the aquatic ecotoxicity impact category.

Table 3-125 through 3-127 list the top contributing flows and their associated processes and life-cycle stages for each impact category for each of the solders. For all categories that are dominated by the use/application stage, except for occupational and public health categories, impacts result from the electricity generation for the wave application process. For the public and occupational health categories, the use/application stage dominates from the actual wave application process. As stated in the previous sections, because the use/application stage is so dominant, a sensitivity analysis of the use/application energy is provided in Section 3.3. Additionally, alternative analyses are conducted with (1) alternative silver production process data, and (2) the results of the less aggressive leachability study for EOL processes. These are also presented in Section 3.3.

The tables show that for each alloy nearly all impact categories are driven by a different flow. Silver production is the primary process driving many of the upstream impacts for SAC, yet as many as six different material flows resulting from silver production are responsible for being the major contributor in any one impact category. For example, suspended solids from silver production drive the water quality impacts, while halon (1301) is the largest contributor to ozone depletion. Only the release of sulfur dioxide to air during extraction and processing of silver is the major contributor in more than one impact category driven by silver production. For SnCu and SnPb bar solders, natural gas and dust releases to air from tin production are the only releases from upstream processes that make up a majority contribution to the impact categories.

There are some flows that are top contributors to more than one impact category, though they may originate from separate processes. For example, sulphur dioxide that drives photochemical smog and air acidification in the SnPb life-cycle is from electricity generation associated with reflow application. In the SAC solder life-cycle, sulphur dioxide is the top contributor to three categories: photochemical smog, air acidification, and public human health (non-cancer). In these cases, however, the sulphur dioxide is from silver production in the upstream life-cycle stage, as opposed to electricity generation for the wave application in the case of SnPb.

Another top flow in the SnPb life-cycle that contributes to more than one category is lead emissions to water from landfilling. This is essentially the leachate from landfilling the SnPb alloy. Lead emissions to water contribute 53.3 percent to the public health (non-cancer) impact category and 71.4 percent to the aquatic ecotoxicity impact category. As mentioned above, refer to Section 3.3 for an alternate analysis of these impacts using a less aggressive leachability test method.

In several instances, the top contributing individual flows comprise a large majority of the total contribution to the alloy's life-cycle impacts within a category. For example, COD constitutes 87.4 percent of the total water eutrophication impacts from SnPb bar solder. As there is not a large amount of chemicals for which there are eutrophication potentials and the inventory in this project only has a few water eutrophying chemicals, it is understandable that one material might greatly dominate impacts. This is true for COD, despite its relatively low eutrophication potential (see Appendix D).

Many top contributors constitute a majority of the total impacts within a category, though the bar solder results are dominated by one flow less than the paste solders. For SnPb solder paste, eleven of the sixteen impact categories had top flows representing a majority of total impacts, while only eight of the sixteen categories for bar solder had a leading contributor of more than fifty percent. SAC and SnCu solders had contributions greater than fifty percent in eight and nine categories respectively.

Table 3-125. 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	SnPb wave application	Flux material F	25.5
Aquatic ecotoxicity	End-of-life	Solder landfilling (SnPb)	Lead emissions to water	71.4

Table 3-126. 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 3-127. 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

3.4.5 Limitations and Uncertainties

3.4.5.1 General LCIA methodology limitations and uncertainties

This section summarizes some of the limitations and uncertainties in the LCIA methodology in general. Specific limitations and uncertainties in each impact category are discussed in Sections 3.2.2 through 3.2.13 with the LCIA results for the LFSP.

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 to 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, and confidentiality issues may inhibit the availability of primary data.

Uncertainties are inherent in each parameter described in Table 3-112 through 3-115. For example, toxicity data require extrapolations from animals to humans and from high to low doses (for chronic effects), resulting in a high degree of uncertainty. Sources for each type of data should be consulted for more information on uncertainties specific to each parameter.

Uncertainties exist in chemical ranking and scoring systems, such 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. Uncertainty is introduced where it was assumed that all chronic endpoints are equivalent, which is likely not the case. In addition, when LOAELs were not available but NOAELs were, a factor of ten was applied to the NOAEL to estimate the LOAEL, thus introducing uncertainty. The human health and ecotoxicity impact characterization methods presented in the LFSP LCIA are screening tools that cannot substitute for more detailed risk characterization methods; however, the methodology is an attempt to consider chemical toxicity at a screening level for potentially toxic materials in the inventory.

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. Uncertainties in the inventory data include, but are 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 assured that some missing data still exist. The remaining uncertainties were reduced primarily through quality assurance/quality control measures (e.g., performing systematic double-checks of all calculations on manipulated data). The limitations and uncertainties in the inventory data were discussed further in Chapter 2.

3.4.5.2 General limitations and uncertainties of results

Limitations and uncertainties in LFSP LCIA results are due to limitations and uncertainties inherent in LCIA methodology itself, as well as limitations and uncertainties in the project LCI data. General limitations and uncertainties in the LCIA methodology were discussed above, and limitations and uncertainties in the project inventory were discussed in Chapter 2. In addition, particular limitations and uncertainties as they pertain to individual impact category results are presented in Sections 3.2.2 through 3.2.13.

The overall limitations and uncertainties associated with the results of each impact category are summarized in Tables 3-117 and 3-123 as relative DQIs. The DQI are qualitative indicators representing a high (H), medium (M), or low (L) level of overall quality, or some combination thereof.

For example, most categories in the paste solder results presented in Table 3-117 are given a medium-to-high relative DQI. Those with lower DQIs include ozone depletion, occupational cancer, and public cancer. Listed below by impact category are the relative DQI measures (in parentheses) and the major sources of uncertainty for those categories:

- Non-renewable and renewable resource use (M-H)—reflow application energy variability and the use of secondary electricity generation data;
- Energy use (H)—reflow application energy variability;
- Landfill space use (M-H)—the use of secondary upstream data;
- Global warming (H)—reflow application energy variability;
- Ozone depletion (L-M)—several ozone depleting chemicals in the inventories (from secondary data sources) are scheduled to have been phased out;
- Photochemical smog, acidification, and air particulates (M-H)—depends somewhat on secondary upstream data;
- Eutrophication and water quality (H)—the use of secondary electricity generation data;
- Occupational and public non-cancer and aquatic ecotoxicity (M-H)—uncertainty in the EOL leachate study; and
- Occupational and public cancer (L-M)—lack of carcinogenicity data for most chemicals.

Details of the uncertainties that contribute to the overall data quality for each impact category are presented in Sections 3.2.2 through 3.2.13.

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APPENDIX A:
LCI DATA COLLECTION FORMS

DESIGN FOR THE ENVIRONMENT
LEAD-FREE SOLDER PROJECT

Life-Cycle Inventory (LCI) Data Collection Form

For Solder Manufacturers

Introduction

The Design for the Environment (DfE) Program in the U.S. Environmental Protection Agency's (EPA) Office of Pollution Prevention and Toxics has begun a voluntary, cooperative project with the electronics industry to assess the life-cycle environmental impacts of solder alternatives. The DfE Program conducts comparative analyses of alternative products or processes to provide businesses with data to make environmentally informed choices about product or process improvements. The DfE Program has no regulatory or enforcement agenda and was established to act as a partner with industry to promote pollution prevention. This environmental life-cycle assessment will address human and environmental impacts (e.g., energy, natural resource use, global warming, chronic toxicity) of various solders. The University of Tennessee (UT) Center for Clean Products and Clean Technologies is conducting the life-cycle inventory (LCI), which is the data collection phase of a life-cycle assessment, with technical assistance from the Electronic Industries Alliance (EIA), IPC -- Association Connecting Electronics Industries, and other partners.

Boundaries

A life-cycle assessment considers impacts from materials acquisition, material manufacturing, product manufacturing, use, and final disposition of a product. The LCI data are intended to be used to evaluate relative environmental impacts over the entire life-cycle of a product. In this project, the product is a type of solder. Therefore, data associated with the materials and processes used directly in the manufacturing, use, and disposition of the product are relevant to the LCI and requested in this form. You will not need to include materials or energy not directly used in the production of the solder (e.g., general building heating and air conditioning).

Product focus

This project will evaluate tin-lead solder (for wave and reflow operations) and consider the following lead-free alternatives:

- -- Sn/Cu (wave)
- -- Sn/Ag/Cu (wave and reflow)
- -- Sn/Ag/Bi or Sn/Ag/Cu/Bi (reflow)

Most recent (or projected) production data are desired.

Inventory data

We are asking for data on one or multiple "product(s) of interest" that you manufacture, which may be one as defined above under Product Focus. The inputs and outputs data (Fig. 1) that you provide will be aggregated in the LCI to quantify the overall inputs and outputs of a solder alternative over its life-cycle. A separate form should be completed for each solder of interest.

Data sources

Much of the requested information can be drawn from existing sources, including, but not limited to the following:

1. Purchase and production records
2. Bills and invoices
3. Material Safety Data Sheets (MSDS)
4. Toxic Release Inventory (TRI) forms
5. Audit and analysis results (e.g., wastewater discharge analyses)
6. Local, state, and federal reporting forms (e.g., hazardous waste manifests)
7. Local, state, and federal permits
8. Monthly utility billing records

How the data will be used

UT will collect inventory data and tally the inputs and outputs for the different solders. Information gathered by this form will be used to develop environmental profiles based on inputs and outputs for the manufacturing stage of the solders. The profiles will be used to evaluate environmental impacts from each product. The environmental profiles can be used to encourage product design changes for product improvement. UT will aggregate data and ensure that data associated with particular companies remain anonymous to the EPA. UT can enter into confidentiality agreements where proprietary data are concerned. Please understand that accurate and representative information from you is critical for the success of this project.

Results of project

The results are intended to provide industry with an analysis of the life-cycle environmental impacts and an analysis of end-of-life issues (e.g., recyclability and leachability) of leaded and lead-free solders. Results will help identify areas for product and process improvement as related to risk and environmental impact (e.g., identifying material use inefficiencies) and will identify impacts from various life-cycle stages of the solders. Use of the results will also help meet growing global demands of extended product responsibility.

Benefits of involvement

As a provider of data, you will be invited to be a member of the project's Technical Workgroup, which reviews interim project reports and is informed of on-going project status. This will allow for your interests to be considered in project development and data collection. By supplying data, the results will partially reflect your operations and, therefore, the results will be directly relevant to your interests. The project will allow you to directly apply results to your manufacturing process and identify areas for improvement and may directly affect industry selection of alterantive solders. You will also be recognized as working voluntarily and cooperatively with the U.S. EPA.

Deadline

The data collection time frame for this project is June 2002 to October 2002. Submission of forms are encouraged as soon as possible; however, we are attempting to obtain all completed forms before October 21, 2002.

Your cooperation and assistance are greatly appreciated.

For any questions, please contact ***Maria Leet Socolof at 865-974-9526*** *, <socolofml@utk.edu> or* ***Jack Geibig at 865-974-6513*** *, <jgiebig@utk.edu> at the University of Tennessee, 311 Conference Center Bldg., Knoxville, TN 37996-4134. Fax: 865-974-1838.*

For more project details, see < http://eerc.ra.utk.edu/ccpct/lfsp.html > and/or the Draft Final Goal Definition and Scoping Document.

INSTRUCTIONS

1. Please be sure to read the introductory text on each page before filling out the form.

2. The data you supply in the tables should represent inputs and outputs associated only with the **"product of interest" (i.e., a solder as defined in the introduction under Product Focus, and what you specify in Table 2, #1)**. If quantities provided are not specific to the "product of interest," please explain how they differ in the comments section at the bottom of the appropriate table. The ultimate goal is to quantify the amount of inputs and outputs per unit (e.g., kg) of solder manufactured.

3. Where supporting information is available as independent documents, reports or calculations, please provide them as attachments with reference to the associated table(s) in this form.

4. If you have more than one product of interest to this project, please duplicate this form and fill out one form for each product.

5. If there is not adequate room on a page to supply your data (including comments), please copy the appropriate page and attach it to this packet.

6. The ensuing pages refer to the following indices to detail specifics about the data. Additional information is provided below as required.
   Data Quality Indicators Index: These indicators will be used to assess the level of data quality in this form. Please report a DQI for the numerical value requested in each table on the following pages. The first category, **Measured**, pertains to a value that is a directly measured quantity. The second category, **Calculated**, refers to a value that required one or more calculations to obtain. The third category, **Estimated**, refers to a value that required a knowledgable employee's professional judgement to estimate. Lastly, the fourth category, **Assumed**, should be used only when a number had to be speculatively estimated.
   Hazardous and Nonhazardous Waste Management Methods Index: These methods are applicable to both hazardous and nonhazardous wastes (Tables 7a and 7b). Please give the appropriate abbreviation in the Management Method column on p. 7 where requested. Depending on whether the management method is on or offsite, please indicate by specifying "on" or "off" in the appropriate column on p. 7.

For Tables 3 - 6:

Data Quality Indicators Index	
M	- Measured
C	- Calculated
E	- Estimated
A	- Assumed

For Tables 6a and 6b:

Wastewater Treatment/Disposal Methods Index	
A	- Direct discharge to surface water
B	- Discharge to offsite wastewater treatment facility
C	- Underground injection
D	- Surface impoundment (e.g., settling pond)
E	- Direct discharge to land
F	- Other (please specify in comments section)

For Tables 7a and 7b (also provided on page 7):

Waste Management Methods Index	
RU	- Reused
R	- Recycled
L	- Landfilled
S	- Solidified/stabilized
Iv	- Incinerated - volume reduction
Ie	- Incinerated - energy conversion
D	- Deep well injected
O	- Other (please specify in comments section)

IF YOU HAVE QUESTIONS, PLEASE CONTACT EITHER:

Maria L. Socolof: Phone: 865-974-9526
Email: socolofml@utk.edu

OR

Jack Geibig: Phone: 865-974-3625
Email: jgeibig@utk.edu

1. FACILITY & CONTACT INFORMATION

Table 1.

Facility Information	Contact Information
1. Company name: ______	4a. Prepared by: ______ Date: ______
2. Facility name: ______	4b. Title: ______
3. Facility address (location): ______	4c. Phone number: ______ Ext.: ______
______	4d. Fax number: ______
______	4e. Email address: ______
______	

5. Major products manufactured onsite and their % of your total production (by weight or volume--and please specify): ______

______

______

2. PRODUCT OF INTEREST INFORMATION

Table 2.

1. Solder of interest (please check one alloy, provide its composition, and complete the form for this alloy).
   Note, if more than one solder listed below is manufactured, please provide a separate form (Tables 2-7) for each solder of interest

☐ Sn/Ag/Cu ____________

☐ Sn/Pb ____________ ☐ Sn/Ag/Bi ____________ [paste]

☐ Sn/Cu ____________ [bar] ☐ Sn/Ag/Cu/Bi ____________ [paste]

2. Solder type (please check): ☐ **Bar** ☐ **Paste**

3. Solder density: ____________

4. Solder melting point: ____________

5. Annual production (past, current, or projected) (e.g., units, kg, lbs): ____________

6. Year (or period of time) for which data are supplied (past, current, or projected): ____________

7. Facility's percent global market share for solder of interest (optional): ____________

8. Brief description of the main operations/subprocesses required to manufacture the product of interest: ____________

____

____

9. From where (what countries) are your base metals supplied (company names optional) and what percent does each location contribute to your supply of each metal? ____________

____

10. Please describe any recommended assembly profiles for your customers for this solder: ____________

11. What % of your solder from your manufacturing process is recycled? ____________ If recycled, (please check): ☐ **ON-SITE** ☐ **OFF-SITE**

a. If recycled on-site, how? ____________

____

b. If recycled off-site, where? (please provide facility name and location if possible): ____________

____

12. Do you accept customer's solder dross for recycling? ☐ **YES** ☐ **NO**

13. Do you accept back other contaminated waste forms specifically to recycle the solder? ☐ **YES** ☐ **NO** If so, what? ____________

14. Have you conducted or do you have any leachability studies on the solder of interest? ☐ **YES** ☐ **NO** If yes, please provide a copy.

3. PRIMARY & ANCILLARY INPUTS

1. Primary & Ancillary Materials: Primary materials are defined as those materials that become part of the final product. Ancillary materials are those material inputs that assist production, yet do not become part of the final product (e.g., cleaning materials). Please include the trade name and the generic name of each material where applicable.
2. CAS # or MSDS: Please include either the CAS (Chemical Abstract Service) number of each material (fill in the blank with the number), or state "MSDS" and append a copy to this document.
3. Annual quantity/units & Density/units: Please specify the annual amount of material consumed in the year of interest (as specified in Table 2, #6). Please use the units of mass-per-year (e.g., kg/yr, lb/yr). If you specify units of volume in lieu of mass, please provide the density. If *annual* quantities are not available, provide applicable units (e.g., kg/1000 kg of product).
4. Data quality indicators: See the Data Quality Indicators Index on p. iii for abbreviations. Please supply the DQI for the *annual quantity* value given.
5. Recycled content: Please specify the recycled content of each material identified. For example, 60/40/0 would represent a material that has 60% virgin material, 40% pre-consumer recycled and 0% post-consumer recycled content. Enter N/A (not applicable) for all components that are assemblies.

Table 3a. **Primary Materials**[1]	**CAS # or MSDS**[2]	**Annual Quantity**[3]	**Units**	**Density**[3]	**Units**	**DQI**[4]	**Recycled Content**[5]
EXAMPLE: GRTX resin (polypropylene resin)	*MSDS*	*450,000*	*kg/yr*	-----	---	*M*	*60/40/0*
1.							
2.							
3.							
4.							
5.							
6.							
7.							

Primary material comments:

Table 3b. **Ancillary Materials**[1]	**CAS # or MSDS**[2]	**Annual Quantity**[3]	**Units**	**Density**[3]	**Units**	**DQI**[4]	**Recycled Content**[5]
EXAMPLE: Petroleum naphtha (cleaning solvent)	*8032-32-4*	*920*	*liters/yr*	*0.96*	*kg/liter*	*C*	*100/0/0*
1.							
2.							
3.							
4.							
5.							
6.							
7.							

Ancillary material comments:

4. UTILITY INPUTS

1. Annual quantity/units: Please specify the amount of the utility consumed in year of interest (as sepcified in Table 2, #6). If possible, please exclude nonprocess-related consumption. If this is not possible, please include a comment that nonprocess-related consumption is included. If *annual* quantities are not available, provide applicable units (e.g., kg/1000 kg of product).
2. Data quality indicators: See the Data Quality Indicators Index on p. iii for abbreviations. Please supply the DQI for the *annual quantity* value given.
3. Individual Utility Notes:
   Electricity:
   The quantity of electricity should reflect only that used toward manufacturing the product of interest (identified on p. 2). One approach would be to start with your facility's total annual electrical energy consumption, remove nonprocess-related consumption, then estimate what portion of the remaining consumption is related to the specific operations of interest. Please include consumption in all systems that use electricity for process-related purposes. Some examples include compressed air, chilled water, water deionization and HVAC consumption where clean or controlled environments are utilized.
   Natural gas and LNG:
   Please exclude all use for space heating or other nonprocess-related uses. If you choose to use units other than MCF (thousand cubic feet), please utilize only units of energy content or volume (e.g., mmBTU, therm, CCF).
   Fuel oils:
   Please use units of either volume or energy content (e.g., liters, mmBTU, MJ). Additionally, if the fuel oil is not delivered by underground pipeline, please include the associated transportation information.
   All waters (e.g., DI, city):
   Please include all waters received onsite. Please indicate consumption in units of mass or volume.

Table 4.	**Utilities[3]**	**Annual Quantity[1]**	**Units**	**DQI[2]**
1.	Electricity		MJ	
2.	Natural gas		MCF	
3.	Liquified natural gas (LNG)		MCF	
4.	Fuel oil - type #2 (includes distillate and diesel)		liters	
5.	Fuel oil - type #4		liters	
6.	Fuel oil - type #6 (includes residual)		liters	
7.	Other petroleum-based fuel		liters	
8.	Water		liters	
9.				
10.				
11.				
12.				
13.				

Utility comments:

5. AIR EMISSIONS

1. Air emissions: The emissions listed in the table below are some of the more common ones found in air release inventories; if you have information on other specific emissions, please provide them in the space provided. If you have any reporting forms or other air emission records for applicable year, please attach copies to this form. Also, if you have information on stack as well as fugitive emissions, please copy this page and place each set of emissions on a different page. The energy consumed in any equipment used onsite to treat air emissions should be included in the utilities values on p. 4.
2. Annual quantity/units: Please specify the amount of air emissions generated and released to the environment in the year of interest (as specified in Table 2, #6). If the emissions data are for a different year, please specify the year in the comments section below. Please use units of mass-per-year (e.g., kg/yr, lb/yr). If *annual* quantities are not available, provide applicable units (e.g., kg/1000 kg of product).
3. Data quality indicators: See the Data Quality Indicators Index on p. iii for abbreviations. Please supply the DQI for the *annual quantity* value given.

Table 5. **Air Emissions**[1]	**CAS number**	**Annual Quantity**[2]	**Units**	**DQI**[3]
Total particulates	-----			
Particulates < 10 microns (PM-10)	-----			
Sulfur oxides (SOx)	-----			
Nitrogen oxides (NOx)	-----			
Carbon monoxide	630-08-0			
Carbon dioxide	124-38-9			
Methane	74-82-8			
Benzene	71-43-2			
Toluene	108-88-3			
Xylenes	1330-20-7			
Naphthalene	91-20-3			
Total nonmethane VOCs	-----			
Other speciated hydrocarbon emissions:	▨	▨	▨	▨
1.				
2.				
3.				
4.				
5.				
6.				
7.				
8.				
9.				
10.				
11.				

Table 5 (continued). **Air Emissions**[1]	**CAS number**	**Annual Quantity**[2]	**Units**	**DQI**[3]
Ammonia	7664-41-7			
Arsenic	7440-38-2			
Chromium	7440-47-3			
Copper	7440-50-8			
Lead	7439-92-1			
Manganese	7439-96-5			
Mercury	7439-98-7			
Nickel	7440-02-0			
Other emissions:	▨	▨	▨	▨
1.				
2.				
3.				
4.				
5.				
6.				
7.				
8.				
9.				
10.				
11.				

Air emission comments:

6. WASTEWATER RELEASES & CONSTITUENTS

1. Annual quantity/units: Please specify the amount of wastewater(s) generated in the year of interest (as specified in Table 2, #6). Please use units of mass-per-year (e.g., kg/yr, lb/yr). If multiple streams exist, please copy this page and fill it out for each stream. If *annual* quantities are not available, provide applicable units (e.g., kg/1000 kg of product).
2. Data quality indicators: See the Data Quality Indicators Index on p. iii for abbreviations. Please include one DQI for the annual wastewater stream quantity value supplied, and one DQI for the wastewater constituents information supplied. If more than one DQI is applicable to the wastewater constituents data, please clarify this in the comment section.
3. Wastewater constituents: Please let us know what type of values you are supplying (e.g., daily maximums, monthly averages, annual averages). Additionally, if you have any reporting forms of other wastewater constituent records for the year of interest, please attach them to this form. The energy consumed in any equipment used onsite to treat wastewater releases should be included in the utilities values on p. 4.
4. Concentration/units: Please specify the concentration of wastewater constituents generated in the year of interest. Please use units of mass-per-volume (e.g., mg/liter, lb/gal).
5. Wastewater treatment/disposal method: See the Wastewater Treatment/Disposal Methods Index on p. iii for method abbreviations.

Table 6a. **Wastewater Stream**	**Annual Quantity[1]**	**Units**	**Treatment/Disposal Method[5]**	**DQI for Annual Quantity**	**DQI for Constituents below**

Table 6b. **Wastewater Constituents[3]**	**CAS number**	**Concentration[4]**	**Units**
Dissolved solids	-----		
Suspended solids	-----		
Carbonaceous Oxygen Demand (COD)	-----		
Biological Oxygen Demand (BOD)	-----		
Oil & grease	-----		
Hydrochloric acid	7647-01-0		
Sulfuric acid	7664-93-9		
Other acids (please specify):	▨	▨	▨
1.			
2.			
Phosphorus			
Phosphates			
Sulfates			
Fluorides			
Cyanide			
Chloride			
Chromium			
Aluminum			
Nickel			

Table 6b (continued). **Wastewater Constituents[3]**	**CAS number**	**Concentration[4]**	**Units**
Mercury			
Lead			
Nitrogen			
Zinc			
Tin			
Ferrous sulfate			
Ammonia			
Nitrates			
Pesticides			
Other speciated constituents:	▨	▨	▨
1.			
2.			
3.			
4.			
5.			
6.			

Wastewater comments:

7. HAZARDOUS & NONHAZARDOUS WASTES

1. Hazardous wastes and EPA hazardous waste numbers: Please list your waste streams that are considered hazardous by the U.S. EPA. Include the hazardous waste codes for any hazardous waste you include.
2. Annual quantity/units & Density/units: Please specify the amount of waste generated in the year of interest (as specified in Table 2, #6). Use units of mass-per-year (e.g., kg/yr, lb/yr). Please also provide the density for each waste. If *annual* quantities are not available, provide applicable units (e.g., kg/1000 kg of product).
3. Data quality indicators: See the Data Quality Indicators Index on p. iii for abbreviations. Please supply the DQI for the *annual quantity* value given.
4. Management method: See key to right of tables for Management Methods Index. If none are applicable, please indicate other and use the comments section to expound.

Table 7a. **Hazardous Wastes**[1]	**EPA Haz. Waste #**[1]	**Annual Quantity**[2]	**Units**	**Density**[2]	**Units**	**DQI**[3]	**Mgmt. method**[4]	**On or offsite?**
EXAMPLE: Spent solvent (toluene)	*F005*	*20,000*	*kg/yr*	*0.9*	*kg/liter*	*M*	*Ie*	*off*
1.								
2.								
3.								
4.								
5.								
6.								
7.								
8.								

Hazardous waste comments:

Table 7b. **Nonhazardous Wastes**	**Annual Quantity**[2]	**Units**	**Density**[2]	**Units**	**DQI**[3]	**Mgmt. method**[4]	**On or offsite?**
EXAMPLE: Waste metal chips	*22,000*	*kg/yr*	*1,000*	*kg/m3*	*C*	*R*	*off*
1.							
2.							
3.							
4.							
5.							
6.							
7.							

Nonhazardous waste comments:

Management Methods Index	
RU	Reused
R	Recycled
L	Landfilled
S	Solidified/stabilized
Iv	Incinerated-volume reduction
Ie	Incinerated-energy conversion
D	Deep well injected
O	Other (specify in comments)

DESIGN FOR THE ENVIRONMENT
LEAD-FREE SOLDER PROJECT

Life-Cycle Inventory (LCI) Data Collection Form

For Solder Recycling Operations

Introduction

The Design for the Environment (DfE) Program in the U.S. Environmental Protection Agency's (EPA) Office of Pollution Prevention and Toxics has begun a voluntary, cooperative project with the electronics industry to assess the life-cycle environmental impacts of solder alternatives. The DfE Program conducts comparative analyses of alternative products or processes to provide businesses with data to make environmentally informed choices about product or process improvements. The DfE Program has no regulatory or enforcement agenda and was established to act as a partner with industry to promote pollution prevention. This environmental life-cycle assessment will address human and environmental impacts (e.g., energy, natural resource use, global warming, chronic toxicity) of various solders. The University of Tennessee (UT) Center for Clean Products and Clean Technologies is conducting the life-cycle inventory (LCI), which is the data collection phase of a life-cycle assessment, with technical assistance from IPC -- Association Connecting Electronics Industries, the Electronic Industries Alliance (EIA), and other partners.

Boundaries

A life-cycle assessment considers impacts from materials acquisition, material manufacturing, product manufacturing, use, and final disposition of a product. The LCI data are intended to be used to evaluate relative environmental impacts over the entire life-cycle of a product. In this project, the product is a type of solder. Therefore, data associated with the materials and processes used directly in the manufacturing, use, and disposition of the product are relevant to the LCI and requested in this form. You will not need to include materials or energy not directly used in the production of the solder (e.g., general building heating and air conditioning).

Product focus

This project will evaluate tin-lead solder (for wave and reflow operations) and consider the following lead-free alternatives:

-- Sn/Cu (wave)
-- Sn/Ag/Cu (wave and reflow)
-- Sn/Ag/Bi or Sn/Ag/Cu/Bi (reflow)

Most recent production data are desired (2001 or 2002).

Inventory data

We are asking for data on one or multiple "product(s) of interest" that you manufacture, which may be one as defined above under Product Focus. The inputs and outputs data (Fig. 1) that you provide will be aggregated in the LCI to quantify the overall inputs and outputs of a solder alternative over its life-cycle. A separate form should be completed for each different type of solder of interest recycled.

Data sources

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UT will collect inventory data and tally the inputs and outputs for the different solders. Information gathered by this form will be used to develop environmental profiles based on inputs and outputs for the end-of-life stage of the solders. The profiles will be used to evaluate environmental impacts from each product. The environmental profiles can be used to encourage product design changes for product improvement. UT will aggregate data and ensure that data associated with particular companies remain anonymous to the EPA. UT can enter into confidentiality agreements where proprietary data are concerned. Please understand that accurate and representative information from you is critical for the success of this project.

Results of project

The results are intended to provide industry with an analysis of the life-cycle environmental impacts and an analysis of end-of-life issues (e.g., recyclability and leachability) of leaded and lead-free solders. Results will help identify areas for product and process improvement as related to risk and environmental impact (e.g., identifying material use inefficiencies) and will identify impacts from various life-cycle stages of the solders. Use of the results will also help meet growing global demands of extended product responsibility.

Benefits of involvement

As a provider of data, you will be invited to be a member of the project's Technical Workgroup , which reviews interim project reports and is informed of on-going project status. This will allow for your interests to be considered in project development and data collection. By supplying data, the results will partially reflect your operations and, therefore, the results will be directly relevant to your interests. The project will allow you to directly apply results to your manufacturing process and identify areas for improvement and may directly affect industry selection of alternative solders. You will also be recognized as working voluntarily and cooperatively with the U.S. EPA.

Deadline

The data collection time frame for this project is May 2002 to November 2002. Submission of forms are encouraged as soon as possible; however, we are attempting to obtain all completed forms before October 21, 2002.

Your cooperation and assistance are greatly appreciated.

For any questions, please contact ***Maria Leet Socolof at 865-974-9526*** *, <socolofml@utk.edu> or* ***Jack Geibig at 865-974-6513*** *, <jgiebig@utk.edu> at the University of Tennessee, 311 Conference Center Bldg., Knoxville, TN 37996-4134. Fax: 865-974-1838.*

For more project details, see the Project Fact Sheet, DfE Website < www.epa.gov/dfe >, or the Draft Final Goal Definition and Scoping Document.

INSTRUCTIONS

1. Please be sure to read the introductory text on each page before filling out the form.
2. The data you supply in the tables should represent inputs and outputs associated only with the **"product of interest" (i.e., a solder as defined in the introduction under Product Focus, and what you specify in Table 2, #1)**. If quantities provided are not specific to the "product of interest," please explain how they differ in the comments section at the bottom of the appropriate table.
3. Where supporting information is available as independent documents, reports or calculations, please provide them as attachments with reference to the associated table(s) in this form.
4. If you have more than one product of interest to this project, please duplicate this form and fill out one form for each product.
5. If there is not adequate room on a page to supply your data (including comments), please copy the appropriate page and attach it to this packet.
6. The ensuing pages refer to the following indices to detail specifics about the data. Additional information is provided below as required.
   Data Quality Indicators Index: These indicators will be used to assess the level of data quality in this form. Please report a DQI for the numerical value requested in each table on the following pages. The first category, **Measured**, pertains to a value that is a directly measured quantity. The second category, **Calculated**, refers to value that required one or more calculations to obtain. The third category, **Estimated**, refers to a value that required a knowledgable employee's professional judgement to estimate. Lastly, the fourth category, **Assumed**, should be used only when a number had to be speculatively estimated.
   Hazardous and Nonhazardous Waste Management Methods Index: These methods are applicable to both hazardous and nonhazardous wastes (Tables 7a and 7b). Please give the appropriate abbreviation in the Management Method column on p. 7 where requested. Depending on whether the management method is on or offsite, please indicate by specifying "on" or "off" in the appropriate column on p. 7.

For Tables 3 - 6:

Data Quality Indicators Index	
M	- Measured
C	- Calculated
E	- Estimated
A	- Assumed

For Tables 6a and 6b:

Wastewater Treatment/Disposal Methods Index	
A	- Direct discharge to surface water
B	- Discharge to offsite wastewater treatment facility
C	- Underground injection
D	- Surface impoundment (e.g., settling pond)
E	- Direct discharge to land
F	- Other (please specify in comments section)

For Tables 7a and 7b (also provided on page 7):

Waste Management Methods Index	
RU	- Reused
R	- Recycled
L	- Landfilled
S	- Solidified/stabilized
Iv	- Incinerated - volume reduction
Ie	- Incinerated - energy conversion
D	- Deep well injected
O	- Other (please specify in comments section)

IF YOU HAVE QUESTIONS, PLEASE CONTACT EITHER:

Maria L. Socolof: Phone: 865-974-9526
Email: socolofml@utk.edu

OR

Jack Geibig: Phone: 865-974-3625
Email: jgeibig@utk.edu

1. FACILITY & CONTACT INFORMATION

Table 1. **Facility Information** **Contact Information**

1. Company/Facility name: ______________________

2. Facility address (location): ______________________

____

____

____

____

4a. Prepared by: ______________________ Date: __________

4b. Title: ______________________

4c. Phone number: ______________________ Ext.: __________

4d. Fax number: ______________________

4e. Email address: ______________________

3. Products produced onsite (e.g., secondary lead, recycled Sn/Pb): ______________________

____

2. PRODUCT OF INTEREST INFORMATION

Table 2.

NOTE: If more than one solder listed in #3 is processed, please provide a separate form for each alloy, if possible

1. What is your major recycled product (e.g., lead, tin, copper)? ____________________

2. Do you accept: ☐ post industrial waste (e.g., dross from printed wiring board assemblers)

   ☐ post consumer waste (e.g., printed wiring boards from disassembled consumer products)

3. What waste solder alloys do you recieve for recycling [check the applicable alloy(s) and provide composition]:

☐ Sn/Pb __________	☐ Sn/Ag/Cu __________
☐ Sn/Cu __________	☐ Sn/Ag/Bi __________
	☐ Sn/Ag/Cu/Bi __________

4. What is your annual production of recycled solder metal (past, current, or projected) (e.g., units, kg, lbs).
   Specify each solder metal that is recycled and the production associated with each metal: ____________________

5. What percent of your operations are associated with processing <u>electronics</u> scrap only? ____________________

6. Year (or period of time) for which data are supplied (past, current, or projected): ____________________

7. Facility's percent global market share for solder of interest (optional): ____________________

8. Briefly describe the main operations/subprocesses required to process the waste solder: ____________________

9. What by-products are produced?

10. If you are processing lead-free solders in your recycling operations, briefly describe how operations differ from processing Sn-Pb (e.g., greater energy demands, greater time, more refining steps): Note, if you are processing lead-free solders separately, please provide all separate tables in this form for each different alloy processed.

3. PRIMARY & ANCILLARY INPUTS

Data for____________________ alloy

1. Primary & Ancillary Materials: Primary materials are defined as those materials that become part of the final product. Ancillary materials are those material inputs that assist production, yet do not become part of the final product (e.g., cleaning materials). Please include the trade name and the generic name of each material where applicable.
2. CAS # or MSDS: Please include either the CAS (Chemical Abstract Service) number of each material (fill in the blank with the number), or state "MSDS" and append a copy to this document.
3. Annual quantity/units & Density/units: Please specify the annual amount of material consumed in the year of interest (as specified in Table 2, #6). Please use the units of mass-per-year (e.g., kg/yr, lb/yr). If you specify units of volume in lieu of mass, please provide the density. If *annual* quantities are not available, provide applicable units (e.g., kg/1000 kg of product).
4. Data quality indicators: See the Data Quality Indicators Index on p. iii for abbreviations. Please supply the DQI for the *annual quantity* value given.
5. Recycled content: Please specify the recycled content of each material identified. For example, 60/40/0 would represent a material that has 60% virgin material, 40% pre-consumer recycled and 0% post-consumer recycled content. Enter N/A (not applicable) for all components that are assemblies.

Table 3a. **Primary Materials**[1]	**CAS # or MSDS**[2]	**Annual Quantity**[3]	**Units**	**Density**[3]	**Units**	**DQI**[4]	**Recycled Content**[5]
EXAMPLE: GRTX resin (polypropylene resin)	*MSDS*	*450,000*	*kg/yr*	-----	---	*M*	*60/40/0*
1.							
2.							
3.							
4.							
5.							
6.							
7.							

Primary material comments:

Table 3b. **Ancillary Materials**[1]	**CAS # or MSDS**[2]	**Annual Quantity**[3]	**Units**	**Density**[3]	**Units**	**DQI**[4]	**Recycled Content**[5]
EXAMPLE: Petroleum naphtha (cleaning solvent)	*8032-32-4*	*920*	*liters/yr*	*0.96*	*kg/liter*	*C*	*100/0/0*
1.							
2.							
3.							
4.							
5.							
6.							
7.							

Ancillary material comments:

4. UTILITY INPUTS

Data for ___________________ alloy

1. Annual quantity/units: Please specify the amount of the utility consumed in year of interest (as sepcified in Table 2, #6). If possible, please exclude nonprocess-related consumption. If this is not possible, please include a comment that nonprocess-related consumption is included. If *annual* quantities are not available, provide applicable units (e.g., kg/1000 kg of product).
2. Data quality indicators: See the Data Quality Indicators Index on p. iii for abbreviations. Please supply the DQI for the *annual quantity* value given.
3. Individual Utility Notes:

Electricity:

The quantity of electricity should reflect only that used toward manufacturing the product of interest (identified on p. 2). One approach would be to start with your facility's total annual electrical energy consumption, remove nonprocess-related consumption, then estimate what portion of the remaining consumption is related to the specific operations of interest. Please include consumption in all systems that use electricity for process-related purposes. Some examples include compressed air, chilled water, water deionization and HVAC consumption where clean or controlled environments are utilized.

Natural gas and LNG:

Please exclude all use for space heating or other nonprocess-related uses. If you choose to use units other than MCF (thousand cubic feet), please utilize only units of energy content or volume (e.g., mmBTU, therm, CCF).

Fuel oils:

Please use units of either volume or energy content (e.g., liters, mmBTU, MJ). Additionally, if the fuel oil is not delivered by underground pipeline, please include the associated transportation information.

All waters (e.g., DI, city):

Please include all waters received onsite. Please indicate consumption in units of mass or volume.

Table 4.

	Utilities[3]	Annual Quantity[1]	Units	DQI[2]
1.	Electricity		MJ	
2.	Natural gas		MCF	
3.	Liquified natural gas (LNG)		MCF	
4.	Fuel oil - type #2 (includes distillate and diesel)		liters	
5.	Fuel oil - type #4		liters	
6.	Fuel oil - type #6 (includes residual)		liters	
7.	Other petroleum-based fuel		liters	
8.	Water		liters	
9.				
10.				
11.				
12.				
13.				

Utility comments:

5. AIR EMISSIONS

Data for ______________________ alloy

1. Air emissions: The emissions listed in the table below are some of the more common ones found in air release inventories; if you have information on other specific emissions, please provide them in the space provided. If you have any reporting forms or other air emission records for applicable year, please attach copies to this form. Also, if you have information on stack as well as fugitive emissions, please copy this page and place each set of emissions on a different page. The energy consumed in any equipment used onsite to treat air emissions should be included in the utilities values on p. 4.
2. Annual quantity/units: Please specify the amount of air emissions generated and released to the environment in the year of interest (as specified in Table 2, #6). If the emissions data are for a different year, please specify the year in the comments section below. Please use units of mass-per-year (e.g., kg/yr, lb/yr). If *annual* quantities are not available, provide applicable units (e.g., kg/1000 kg of product).
3. Data quality indicators: See the Data Quality Indicators Index on p. iii for abbreviations. Please supply the DQI for the *annual quantity* value given.

Table 5. **Air Emissions**[1]	**CAS number**	**Annual Quantity**[2]	**Units**	**DQI**[3]
Total particulates	-----			
Particulates < 10 microns (PM-10)	-----			
Sulfur oxides (SOx)	-----			
Nitrogen oxides (NOx)	-----			
Carbon monoxide	630-08-0			
Carbon dioxide	124-38-9			
Methane	74-82-8			
Benzene	71-43-2			
Toluene	108-88-3			
Xylenes	1330-20-7			
Naphthalene	91-20-3			
Total nonmethane VOCs	-----			
Other speciated hydrocarbon emissions:	▨	▨	▨	▨
1.				
2.				
3.				
4.				
5.				
6.				
7.				
8.				
9.				
10.				
11.				

Table 5 (continued). **Air Emissions**[1]	**CAS number**	**Annual Quantity**[2]	**Units**	**DQI**[3]
Ammonia	7664-41-7			
Arsenic	7440-38-2			
Chromium	7440-47-3			
Copper	7440-50-8			
Lead	7439-92-1			
Manganese	7439-96-5			
Mercury	7439-98-7			
Nickel	7440-02-0			
Other emissions:	▨	▨	▨	▨
1.				
2.				
3.				
4.				
5.				
6.				
7.				
8.				
9.				
10.				
11.				

Air emission comments:

6. WASTEWATER RELEASES & CONSTITUENTS

Data for ________________________ alloy

1. Annual quantity/units: Please specify the amount of wastewater(s) generated in the year of interest (as specified in Table 2, #6). Please use units of mass-per-year (e.g., kg/yr, lb/yr). If multiple streams exist, please copy this page and fill it out for each stream. If *annual* quantities are not available, provide applicable units (e.g., kg/1000 kg of product).
2. Data quality indicators: See the Data Quality Indicators Index on p. iii for abbreviations. Please include one DQI for the annual wastewater stream quantity value supplied, and one DQI for the wastewater constituents information supplied. If more than one DQI is applicable to the wastewater constituents data, please clarify this in the comment section.
3. Wastewater constituents: Please let us know what type of values you are supplying (e.g., daily maximums, monthly averages, annual averages). Additionally, if you have any reporting forms of other wastewater constituent records for the year of interest, please attach them to this form. The energy consumed in any equipment used onsite to treat wastewater releases should be included in the utilities values on p. 4.
4. Concentration/units: Please specify the concentration of wastewater constituents generated in the year of interest. Please use units of mass-per-volume (e.g., mg/liter, lb/gal).
5. Wastewater treatment/disposal method: See the Wastewater Treatment/Disposal Methods Index on p. iii for method abbreviations.

Table 6a. **Wastewater Stream**	**Annual Quantity[1]**	**Units**	**Treatment/Disposal Method[5]**	**DQI for Annual Quantity**	**DQI for Constituents below**

Table 6b. **Wastewater Constituents[3]**	**CAS number**	**Concentration[4]**	**Units**
Dissolved solids	-----		
Suspended solids	-----		
Carbonaceous Oxygen Demand (COD)	-----		
Biological Oxygen Demand (BOD)	-----		
Oil & grease	-----		
Hydrochloric acid	7647-01-0		
Sulfuric acid	7664-93-9		
Other acids (please specify):	▨	▨	▨
1.			
2.			
Phosphorus			
Phosphates			
Sulfates			
Fluorides			
Cyanide			
Chloride			
Chromium			
Aluminum			
Nickel			

Table 6b (continued). **Wastewater Constituents[3]**	**CAS number**	**Concentration[4]**	**Units**
Mercury			
Lead			
Nitrogen			
Zinc			
Tin			
Ferrous sulfate			
Ammonia			
Nitrates			
Pesticides			
Other speciated constituents:	▨	▨	▨
1.			
2.			
3.			
4.			
5.			
6.			

Wastewater comments:

7. HAZARDOUS & NONHAZARDOUS WASTES

Data for _________________________ alloy

1. Hazardous wastes and EPA hazardous waste numbers: Please list your waste streams that are considered hazardous by the U.S. EPA. Include the hazardous waste codes for any hazardous waste you include.
2. Annual quantity/units & Density/units: Please specify the amount of waste generated in the year of interest (as specified in Table 2, #6). Use units of mass-per-year (e.g., kg/yr, lb/yr). Please also provide the density for each waste. If *annual* quantities are not available, provide applicable units (e.g., kg/1000 kg of product).
3. Data quality indicators: See the Data Quality Indicators Index on p. iii for abbreviations. Please supply the DQI for the *annual quantity* value given.
4. Management method: See key to right of tables for Management Methods Index. If none are applicable, please indicate other and use the comments section to expound.

Table 7a. **Hazardous Wastes**[1]	**EPA Haz. Waste #**[1]	**Annual Quantity**[2]	**Units**	**Density**[2]	**Units**	**DQI**[3]	**Mgmt. method**[4]	**On or offsite?**
EXAMPLE: Spent solvent (toluene)	*F005*	*20,000*	*kg/yr*	*0.9*	*kg/liter*	*M*	*Ie*	*off*
1.								
2.								
3.								
4.								
5.								
6.								
7.								
8.								

Hazardous waste comments:

Table 7b. **nhazardous Wastes**	**Annual Quantity**[2]	**Units**	**Density**[2]	**Units**	**DQI**[3]	**Mgmt. method**[4]	**On or offsite?**
EXAMPLE: Waste metal chips	*22,000*	*kg/yr*	*1,000*	*kg/m3*	*C*	*R*	*off*
1.							
2.							
3.							
4.							
5.							
6.							
7.							

Nonhazardous waste comments:

Management Methods Index

RU	Reused
R	Recycled
L	Landfilled
S	Solidified/stabilized
Iv	Incinerated-volume reduction
Ie	Incinerated-energy conversion
D	Deep well injected
O	Other (specify in comments)

APPENDIX B:
USE/APPLICATION ENERGY TESTING

- Geibig, J., M. Socolof, P. Paulraj, and T. Brady. "Life-Cycle Impacts of Energy Consumption during Reflow Assembly of Electronics using Lead-Free Solders," IPC APEX 2003, Anaheim, California.

Life-Cycle Impacts of Energy Consumption during Reflow Assembly of Electronics Using Lead-Free Solders

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Abstract— The energy consumed during the reflow assembly of printed wiring board assemblies is expected to be environmentally significant within the solder product life-cycle. Wide differences in the melting temperatures of lead and lead-free solders alternatives suggests that there may be large and important tradeoffs associated with the selection of solder and its ultimate impact on the environment. Preliminary results of testing, conducted as part of an overall life-cycle assessment of lead and lead free solders, are presented in this paper and then compared to previously conducted studies. Life-cycle impacts associated the test data are also presented.

Testing results indicate that energy consumption can vary by as much as 40 percent across alternative solders, with the National Electronics Manufacturing Initiative (NEMI) recommended Sn/Ag/Cu alloy consuming eight percent more energy than eutectic Sn/Pb, and the Sn/Ag/Bi alloy consuming as much as 32 percent less energy. Although absolute energy consumption values during this test were higher than other studies, relative energy differences between solder types strongly agreed with those of previous studies. Finally, the environmental impacts associated with the energy consumed during reflow assembly were demonstrated to be significant when compared energy use in upstream life-cycle processes.

INTRODUCTION

Adoption of lead-free solders for the manufacturing of electronics presents the industry with many challenges. One such challenge results from the elevated melting points of the leading solder alternatives and the changes required in the associated assembly profiles. More energy is likely required to maintain the higher oven temperatures required to melt and then reflow these solders during assembly, resulting in increased costs to assemblers and potential environmental impacts [1, 2].

The University of Tennessee has partnered with the US EPA Design for the Environment Program, non-government organizations, and members of the electronics industry to evaluate the life-cycle environmental and human health impacts of lead and lead-free solder use in the electronics industry. The primary goal of the project is to conduct a detailed life-cycle assessment (LCA) of leading solder alternatives that considers the impacts associated with the entire product system. For solder, the product system life-cycle stages include materials extraction and processing of the metal ore, manufacturing of the solder, application of the solder during assembly, and the final disposition of the solder as part of waste electronics.

Primary life-cycle impacts occurring during the solder application life-cycle stage are expected to result from the energy consumed during the reflow assembly process [2, 3]. To assess the environmental consequences of a change in solders during reflow, project partners conducted testing at an Intel facility to estimate the energy consumed during the reflow assembly of printed wiring boards (PWBs) using select lead and lead-free solders. This paper presents the findings of the testing and compares the results to the energy consumed from other upstream life-cycle processes.

SOLDER REFLOW TEST METHODOLOGY

Development of a testing protocol was performed in cooperation with a group of industry experts knowledgeable about reflow assembly as well as the overall goals of the LCA project. The advisory group included representatives from solder suppliers, equipment manufacturers, and electronics manufacturers with in-house assembly capability. The developed protocol balanced the need to collect data in a timely and cost efficient manner with the desire to capture 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 printed wiring board (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 cost of operation. Therefore, testing was confined to the measurement of power consumption during periods of steady-state operation, neglecting the preheat cycle.

Solders for evaluation were selected with the overall objectives of the LCA study in mind, and include the solders selected for evaluation in the larger LCA study. Solder alloys compositions evaluated during the testing include:

- Sn/Pb - 63/37
- Sn/Ag/Bi (SAB) - 42/1/57
- Sn/Ag/Cu (SAC) - 95.5/3.9/0.6

As a result of prior testing at 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 the bismuth-containing solder. A suggested profile for the bismuth-containing solder 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 1.

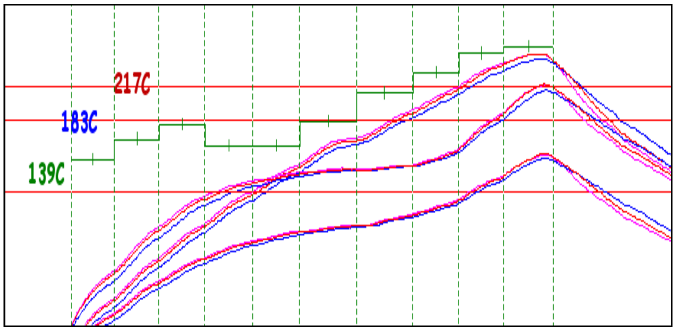

Figure 1. Solder Reflow Profiles

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 1.

Table 1. Reflow Profile Specifications

Solder	**Peak Temperature (range)**	**TAL (average)**	**δ Temp**
Sn/Ag/Bi	160.2-170.1C	65 secs	9.9C
Sn/Pb	204.4-219.1C	51 secs	14.7C
Sn/Ag/Cu	235.2-248.8C	65 secs	13.6C

An Intel micro ATX motherboard that had been previously assembled was selected as the test assembly for this testing. The motherboard was selected as a baseline for testing because it is at the upper end of applications typical for the consumer electronics market in terms of size, mass and complexity.

Because solder reflow occurs once the joint reaches the minimus temperature required for the particular solder, and because the scope of our testing was limited to energy consumption and not joint testing, preassembled boards were used to limit the cost of the testing. A photo of the test board is shown in Figure 2. Specifications for the test assembly are presented in Table 2.

Figure 2. Reflow test PWB assembly

Table 2. Test Vehicle Specifications

PWB Type	Micro ATX Motherboard
Length	9.6 inches
Width	9.6 inches
Mass of Assembly	225 grams
Mass of Solder (estimated)	2.5 grams/board

Testing was conducted at the Intel facility in Hillsboro, Oregon using a ten zone forced convection reflow oven with an attached water-cooled chiller unit to cool the assemblies following reflow. Energy measurements were taken at the main power feeds to both the oven and chiller using appropriately sized transducers and a data logger. 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. Energy measurements were taken from the time the first assembly entered the oven until the final assembly exited the chiller, a test run duration of thirteen minutes. Assemblies exiting the oven were allowed to reach room temperature before being reintroduced to the oven for the next test run.

TESTING RESULTS

Results from the reflow testing are presented in Table 3 below, along with the results from a similar study conducted by the National Electronics Manufacturing Initiative (NEMI) [4].

Table 3. Energy Consumption during Reflow Testing

Solder	UT/ Intel (kW)	% Change from Baseline	NEMI (kW)	% Change from Baseline
Sn/Ag/Bi	15.7	-32.5	N/A	---

Sn/Pb	23.3	---	14.8	---
Sn/Ag/Cu	25.2	8.3	16.5	11.5%

Testing results indicate that there are significant differences in the amounts of energy required to reflow the various solders under our test conditions. For example, as compared to eutectic Sn/Pb solder, the SAC alloy consumed 8.3 percent more energy over the same period of process operation. This is mostly due to the elevated melting point (218 °C) of the SAC alloy, which is a full 35 °C higher than that of the eutectic Sn/Pb alloy. The increased temperature not only results in higher energy consumption during reflow, but also requires the re-engineering of most PWB surface components which can fail under the higher temperature reflow cycle.

By contrast, the SAB alloy consumed nearly 33 percent less energy over the same test period. This is largely due to the influence of the high concentration of bismuth in the solder that acts to reduce the overall melting point of the alloy to 138 °C, a full 45 °C less than the melting point for the Sn/Pb eutectic. Still, the results relative to the other solders are somewhat lower than can be attributed simply to the decreased melting point. The larger decrease may also involve other factors such as higher oven efficiency at the lower temperature, and less energy loss from the oven due to PWB throughput. In addition, the peak reflow temperature of 179 °C for the high bismuth alloy does not approach the typical reflow temperatures used for Sn/Pb, making the full range of currently approved components available for assembly without concern for increased component failure rates.

Results from similar testing conducted as part of the research activities of the NEMI Lead-Free Component team have also been displayed in Table 4 for comparison purposes. As shown in the table, the data presented in this paper are higher than those reported by the NEMI group [4]. Other studies, both published and unpublished confirm this disparity [5, 6, 7]. However, while the absolute energy values are higher, the relative energy consumption among the different solder alloys reported in this work agrees very well with that of the other studies. At the time of this writing, the authors are investigating the source of disparity between the reported data sets, but are uncertain as to the cause due to our unfamiliarity with the other studies. Possible sources of disparity may include the use of less efficient, older reflow equipment, testing protocols, and differences in the conditions under which testing occurred (e.g. reflow profiles). The NEMI study did not include the SAB alloy so no comparison can be made to the data collected in this study for that alloy.

An attempt was made to characterize the magnitude of energy loss to the system attributable to the mass of PWB assembly passing through the reflow zone. This ‘heat sink’ affect is not solely attributable to the mass of the solder, but rather is related to the mass of the overall assemblies and the individual characteristics of the materials involved. By comparing the energy consumption of the reflow ovens under loaded and unloaded conditions, the amount of additional energy required due to the work being passed through the system is estimated and presented in Table 4 below.

Table 4. Baseline Reflow Oven Power Consumption

Solder	Unloaded (kW)	Loaded (kW)	% of Total Energy Due to Loading
Sn/Ag/Bi	15	15.7	4.5
Sn/Pb	20.9	23.3	10.3
Sn/Ag/Cu	22.2	25.2	11.9

These results apply only to the PWB assembly used in this testing. However, they also provide a snapshot against which other board designs and configurations may be compared to assess the potential magnitude of their respective energy consumption and the potential range of values possible.

LIFE CYCLE COMPARISON

Results from the energy consumption testing reported in the previous section were combined with energy data collected from other life-cycle stages to assess the impacts of energy use within the product life-cycle. Sources of energy included in this evaluation were electricity from the US power grid, heavy fuel oil, and natural gas. Energy values within each life-cycle stage were converted to a common value of megajoules (MJ) and then combined to obtain an energy use for the entire life-cycle stage. To facilitate comparison of the energy use across life-cycle stages and for different solders, a functional unit based on the volume of solder was used to normalize all data. The volumes were converted to mass using the density of the solder alloys, and all data adjusted and reported in energy use per mass of solder processed.

Life-cycle impacts resulting from energy use were calculated and presented for the materials extraction & processing (e.g. diesel to power mining equipment), solder manufacturing (e.g. natural gas to fire the refining pots), and solder application life-cycle stages. Since end-of-life (EOL) energy use data (e.g. electricity to power shredders) are not yet completely collected and aggregated, impacts from end-of-life were not included in this evaluation. The resulting data by life-cycle stage for each solder are presented in Figure 3.

The figure shows that the energy consumed during the application and assembly of the PWB’s dominate, with results ranging from ranging from 91-96 percent of the overall life-cycle energy, depending on the solder type. Unlike with the other life-cycle stages where the energy consumption is tightly linked to the mass of solder produced, the energy consumed during the reflow application stage is a function of the physical characteristics of the solder alloy, and only minutely affected by the mass of solder processed. The differences in energy consumption between life-cycle stages become magnified after the data are normalized by the mass of solder produced.

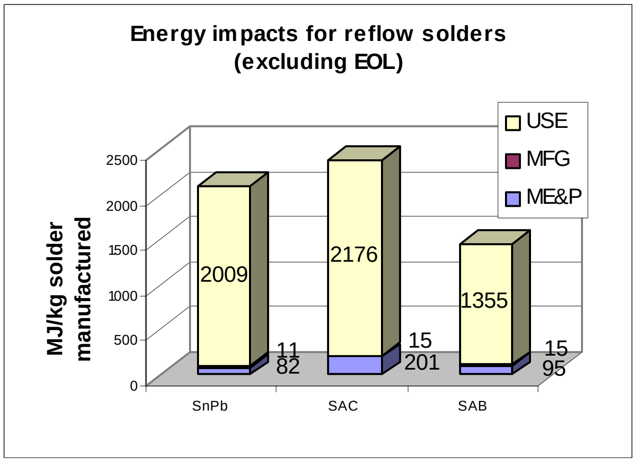

Figure 3. Life-Cycle Energy Use (excluding EOL)

Our testing found a higher rate of energy use during reflow than other reported data. For purposes of comparison, the NEMI data were substituted for the project test data and the life-cycle energy use was recalculated. The results are shown in Figure 4.

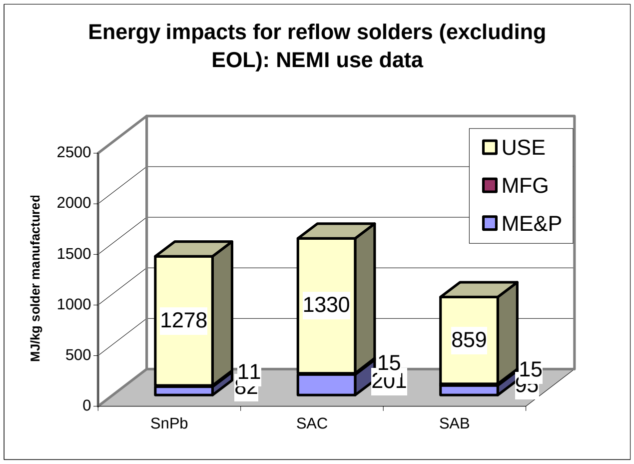

Figure 4. Life-Cycle Energy Use (excluding EOL) using NEMI Testing Data

As can be seen, while the overall values dropped considerably, the energy use during reflow still dominated the energy use category. Values ranged from a low of 86 percent for SAC to a high of 93 percent for Sn/Pb solder.

An analysis was conducted on the data to determine the sensitivity of the energy use data to variations in the mass of solder applied to the PWB. It was determined that PWB's would have to contain nearly 27 grams of SAC or over 60 grams of Sn/Pb solder per PWB assembled for the normalized energy use from reflow soldering to approach that of the other life-cycle stages. Since the mass of solder applied to a typical PWB in the consumer market ranges from 1-3 grams [3, 8], the energy consumption from the application stage appears to dominate within the range of typical assembly conditions.

Energy use has several environmental consequences, among them global warming. As an example of the importance of energy consumption within the life-cycle, the global warming impacts from energy consumption were calculated and presented here. Global warming results from a build-up of CO_2 and other greenhouse gases that are emitted to the atmosphere, some during the production of electricity and other energy sources. Global warming impacts are calculated using the mass of greenhouse gases released to the atmosphere, which are then modified using a global warming potential equivalency factor. The equivalency factor is an estimate of the chemical's atmospheric lifetime and radiative forcing referenced to a common chemical, in this case CO_2 [9].

Global warming impacts were calculated for the life-cycle energy use excluding EOL energy consumption, and presented in Figure 5. The results indicate that the energy consumed during reflow assembly of the solder is the primary influence on global warming impacts. The reflow application of solder is responsible for from 91-96 percent of the global warming impacts, depending on the solder type. While the results are preliminary and do not include the EOL processes, it is expected that this trend will hold once EOL is included in the data set, due to the enormous amount of energy required during assembly as compared to the other life-cycle stages.

DISCUSSION OF RESULTS

Energy use during the reflow process was demonstrated by this research to be a critical factor in the assessment of the overall environmental footprint of the solder product system. The test data indicate that the energy use during solder reflow assembly, once normalized for mass of solder processed, accounts for as much as 96 percent of the total energy consumed over the entire life-cycle, excluding EOL.

Energy consumption was found to vary significantly between solder alloys, primarily due to the difference in melting points and the corresponding changes in the reflow profile design parameters. Testing indicated that soldering with the SAC alloy would result in an 11 percent increase in reflow energy use and an overall increase in life-cycle energy consumption of 13.8 percent when compared to Sn/Pb. Conversely, soldering with the SAB alloy would result in a reduction in energy use of nearly 30 percent over that of Sn/Pb over the same life-cycle stages.

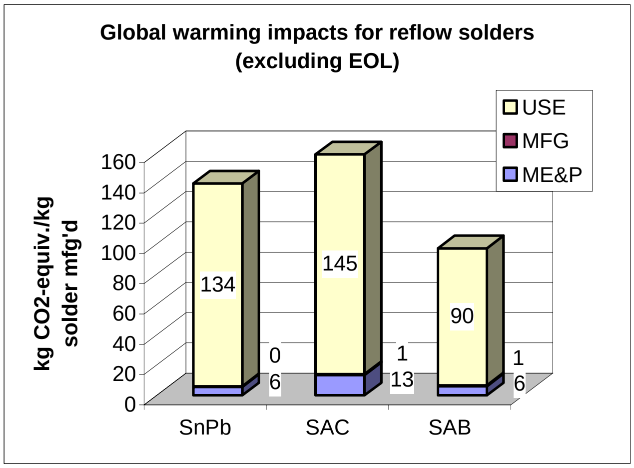

Figure 5. Global Warming Impacts from Energy use During Application

Normalizing the energy data by the mass of solder processed allows for comparison of the energy consumption across life-cycle stages, but also result in the data being sensitive to small variations in the mass of solder per board. This is problematic to the LCA study since the energy required is mostly dependent on the physical properties and flow characteristics of the alloy. There exists, at best, a tangential and fairly inconsequential correlation between the mass of solder and the total energy consumed during reflow. A sensitivity analysis was conducted to determine the potential affect of variation in the mass of solder per board processed on the calculated environmental impacts. Results of the analysis indicated that under typical electronics manufacturing scenarios the overall energy use would remain dominated by the reflow application stage.

Global warming impacts resulting from the life-cycle energy consumption (excluding EOL) were calculated and presented. As expected, the global warming impacts mirrored the relative energy use of the individual solder alloys.

Finally, the results of this study emphasize the importance of continued research into reflow techniques and equipment advances to further reduce the environmental footprint of the process. Although energy during reflow can often be achieved through process engineering techniques, such as by slowing the conveyor speed, the overall amount of energy per mass of solder may actually increase due to the reduced production of the process line.

ACKNOWEDGEMENTS

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APPENDIX C:
SOLDER LEACHABILITY TESTING

- Townsend, T. "Leachability of Printed Wiring Boards Containing Leaded and Lead-Free Solder." Report prepared for Abt Associates in support of the Lead-Free Solder Project, March, 2005.

Leachability of Printed Wire Boards Containing Leaded and Lead-Free Solder

Report Presented To:

Abt Associates Inc.
Project Manager: Cheryl Keenan

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May 30, 2003
(Updated March 8, 2005)

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1.0 Introduction

Major components of electronic devices are printed wiring boards (PWBs). Metallic solder is a major component of a printed wiring assembly (PWA), which is the PWB populated with components. The prevalent solder type used on most PWBs is a tin-lead solder. The presence of lead raises several environmental concerns, including the fate of the lead upon disposal of the discarded electronic device. Alternative solder types are available. Examples include tin-copper and tin-silver-copper. The U.S. EPA's Design for the Environment Program has worked with stakeholders to examine the life-cycle environmental impacts of tin-lead and lead-free solders. As part of this effort, a life-cycle assessment (LCA) is being conducted by the University of Tennessee. The impact and fate of the chemicals in the different solder types upon landfill disposal is an important consideration in the LCA.

To support the PWB solder LCA, laboratories at the University of Florida were contracted to conduct regulatory leaching tests on PWBs manufactured with five alternative solder types. The two leaching tests performed were the toxicity characteristic leaching procedure (TCLP) and the synthetic precipitation leaching procedure (SPLP). Both tests were developed by the U.S. Environmental Protection Agency and are often used in waste management decision making. The application and limitations of these tests are discussed. The five solder types investigated include:

- 63% Sn/ 37%Pb,
- 99.3% Sn / 0.7% Cu,
- 95.5% Sn / 4.0% Ag / 0.5% Cu,
- 96.0% Sn/ 2.5% Ag / 1.0% Bi / 0.5% Cu,
- 42.0% Sn/ 1.0% Ag / 57.0% Bi.

TCLP and SPLP tests were conducted on four different PWB sections, each with a unique configuration and solder density.

2.0 Background

2.1 The Motivation for Leaching Tests

Toxic heavy metals in process waste or discarded product have the potential to impact human health and the environment when those materials are managed improperly. The potential risk posed, however, cannot always be simply judged by the total amount of metals that are present. For some wastes, the heavy metals may be bound or encapsulated in such a fashion that they do not migrate from the waste when disposed. Leaching tests are typically used to assess the potential for heavy metals (or other chemicals) to migrate or leach from a solid waste in different disposal scenarios.

2.2 Considerations in Selecting Leaching Test Methodology

Several different leaching test methodologies have been developed by regulatory or testing agencies, or have been described in published literature. Some leaching methods are relatively simple and rapid. In these tests, wastes are exposed to a leaching solution in a laboratory container under a prescribed set of conditions and the concentrations of metals in the solution are measured after a specified time of exposure. Others evaluate the leaching of metals from wastes by constructing simulated disposal environments (such as a landfill), and observing the concentrations of the metals of concern over time.

The selection of an appropriate leaching test depends on several considerations. The objective of the leaching test is a paramount consideration. The specific use of a particular leaching test also may be required as part of a regulatory application (see the discussion of the TCLP below). For assessing the possible impact from co-disposal of a waste on landfill leachate concentrations, simple laboratory tests provide an adequate indication of how metals might leach from the waste. However, since so many factors impact metal leachability from a waste (e.g., pH, oxidation reduction potential), simple tests cannot account for all conditions that occur in a landfill. More elaborate testing protocols (e.g., lab testing under multiple testing conditions, simulated landfill experiments) may be required. Cost and time are also a major consideration in leach testing. While more elaborate testing requirements may provide more realistic results, they are more expensive and may be much more time-consuming.

Two relatively simple leaching tests are the TCLP and SPLP. The procedures are similar with the exception of the leaching fluid used. They are described in greater detail in the following sections. The rationale for selecting these tests is also discussed.

2.3 TCLP

The TCLP, EPA Method 1311, uses an acetic acid solution to simulate conditions in a municipal waste landfill where organic acids are produced as a result of waste decomposition. The TCLP requires 100 g of material for the test and the material must be size-reduced prior to leaching. Leaching takes place at a 20:1 liquid to solid ratio in a rotary extractor at 30 rpm for 18 hours. The leachates are then filtered and analyzed for the chemicals of concern.

2.4 SPLP

The SPLP, EPA Method 1312 is similar in nature to the TCLP, but utilizing a leaching fluid designed to simulate acid rainfall. It contains trace amounts of nitric and sulfuric acids. The TCLP is used to make hazardous waste determinations. The SPLP is frequently used to assess risk from environments where large amounts of organic acids are not expected to be produced (beneficial use through land application, near surface soil leachate).

2.5 Rationale for Selection of Leaching Experiments

The objective of the research was to evaluate the extent to which metals leach from PWBs assembled with different solder types. Data developed during testing would then be used to inform the LCA on potential end-of-life releases from PWBs disposed by landfilling. However, only minimal data regarding leaching of metals from PWBs with different solder types have been reported previously, the TCLP and SPLP were selected to provide a means of leaching a large number of samples over a range of conditions. The TCLP and SPLP have been found in many cases to bracket the range of leaching concentrations encountered when wastes are leached with actual landfill leachate.

3.0 Methods

3.1 Materials Tested

To assess the effects of PWB configuration on leachability, three different PWB types were selected from boards donated by industry based on their varied specifications. Solder was applied to the PWBs prior to their shipment to the University of Florida by passing the unpopulated boards through the appropriate assembly process. Unpopulated boards were used to prevent metal contamination from components and to ensure that the results reflect only the contributions from the applied solder. The PWB types selected for leachability testing are described as follows:

- A large multi-layer PWB with a variable surface circuit density (designated board type AB)
- A small PWB with a uniform high solder population density (designated as board type C)
- A small PWB with a uniform low population solder density (designated as board type D)

Solders applied to each of the PWB types to be tested included:

- 63% Sn / 37% Pb
- 57.0% Bi/ 42.0% Sn/ 1.0% Ag
- 95.5% Sn / 4.0% Ag / 0.5% Cu
- 96.0% Sn/ 2.5% Ag / 1.0% Bi / 0.5% Cu
- 99.3% Sn / 0.7% Cu

One PWB of each type was also provided with no solder applied to the surface. These unsoldered PWBs were used as sample "blanks." For boards C and D, the board types were slightly different for the Sn-Pb and Bi/Sn/Ag solder as compared to the other three solder types. The difference was minor but was observed in the weights of the populated and blank boards.

As will be discussed below, the TCLP and SPLP each require 100 g of sample. One hundred-gram sections of board type C and board type D were identified and used as samples. Two different 100-g sections of board type AB were identified and used as samples (designated as board samples A and B). Thus a total of 4 different board samples were tested (A, B, C and D).

3.2 Sample Processing

The TCLP and SPLP require that samples be size-reduced to less than 0.95 cm. Size-reduction of the PWBs was performed using an industrial metal press. The dimensions and weights of each board were measured upon receipt. The weight data were used to estimate the board-solder density. One hundred-gram board sections were identified and these were used as the actual samples. These samples were cut into small squares to meet the size reduction requirement. To protect against contamination of the samples, the surface and blade of the metal press were washed with nitric acid before and during the cutting process.

In the case of samples C and D, the initial weight of each board type was slightly over 100 g, the size requirement for the TCLP and SPLP. Thus only a small piece on the edge of the board was identified and removed to bring the weight of the boards to approximately 100 g. The same piece was removed in each case. The remainders of the C and D boards were then size-reduced to meet the requirements of the leaching tests.

The AB boards weighed several times more than 100 g. Thus, two target areas were identified based on a visual inspection and the overall density of the boards. Board sample A was selected from a section of the board with a higher solder density than board sample B (based on visual inspection). Appendix C.2 presents a photo with the approximate location of each section of the board noted. The same area was cut from each board so that the same architecture was captured for each sample (i.e. the same amount of solder points were captured).

In both cases, because of a slight variability among the densities of each board, the final weights of each sample differed slightly. This was accounted for in the later testing by maintaining the liquid to solid ratio of 20:1 as required by the leaching tests.

3.3 Leaching Tests

The TCLP and SPLP are similar, but use different leaching fluids. The TCLP extraction solution was prepared by diluting a mixture of 11.4 mL of acetic acid (CH3COOH) and 128.6 mL of 1N sodium hydroxide (NaOH) to two liters using reagent water. The final pH of the solution was 4.93 ± 0.05. The SPLP leaching solution was prepared by mixing 60 g of sulfuric acid with 40 g of nitric acid. The SPLP extraction fluid was prepared by adding between 0.4 and 0.5 mL of the sulfuric acid / nitric acid mixture to a 2 L volumetric flask and diluting it to volume with reagent water. The resultant pH was 4.22 +/- 0.05. The leaching tests involved placing 100 g of reduced size PWB into a 2.2-liter extraction vessel, adding two liters of leaching solution to the vessel, tumbling for 18 ± 2 hrs, and filtering the extract using a pressurized filtration apparatus with a 0.7-μm borosilicate glass fiber filter (Environmental Express TCLP filters).

3.4 Leachate Analysis

After filtration, the extract was digested (U.S. EPA Method 3020A). The digestates were first analyzed for Pb, Ag, Cu, and Sn using a Thermo Jarrell Ash ICAP 61E Tracy Analyzer. This instrument was not, however, equipped to analyze for bismuth. Thus, the digestates were analyzed a second time using flame atomic absorption (FLAA) spectrometry using a Perkin-Elmer 5100 Atomic Absorption Spectrophotometer. While the detection limits for each element were below the RCRA toxicity characteristic concentration (TC) limit (for determining whether a solid waste is a TC hazardous waste), many of the initial results were below detection limit, even for samples where the elements were known to be a part of the solder. Thus, many of the samples were re-digested for analysis using a graphite furnace, and were reanalyzed using this more sensitive technique (the Perking Elmer 5100 Atomic Absorption Spectrophotometer). Laboratory blanks, sample spikes, field duplicates, and calibration check samples were performed as appropriate.

3.5Estimation of Solder Density

The UF labs were asked to estimate the solder density of the various samples tested (solder density being defined as the percent of board by weight consisting of solder). The first attempt to do this was conducted by weighing each board as received, weighing the blank boards, and then subtracting the weights to determine solder weight. This method was found to be unsatisfactory for samples A and B. This resulted from the relatively small weight of solder on the boards (relative to the boards themselves) and because of inherent weight differences even between like boards. Solder density estimates for samples C and D represent the solder density over the entire PWB since the PWBs themselves weighed only slightly more than the 100 g required for the leaching tests. Even the results of the D board tests, however, were questionable because of the relatively small fraction of solder contained. Inherent differences in overall board weight could have an impact on accuracy of measurements of small solder weights.

In an effort to get a more accurate estimate of the solder densities of boards A, B, and D, sections of these boards from extra samples were digested in acid and the metal content was measured. Specifically, Bi-Sn-Ag board samples were digested and the mass of solder was estimated based on the amount of bismuth measured in the digestate. The volume of solder required to assemble a PWB is a function of both the PWB design and the geometry of the solder connections required. Therefore, the mass of each of the solders for each PWB sample type were estimated using the ratio of the appropriate solder density (i.e. the density for the type of solder the PWB was assembled with) to the density of the Bi-Sn-Ag solder. The solder mass for each sample was then used to calculate the percentage of the overall sample weight (roughly 100 g) that was comprised of solder. These estimated densities for PWB samples undergoing leachability testing are presented in Table 1. Within each solder type (i.e. each column of the table) the board type with a higher solder density would be expected to leach more metal because of the higher concentration of metal in the given 100-g sample size consistent across PWB types. It is noted that there is no standardized digestion procedure for digesting whole boards.

Table 1. Estimated Solder Densities of PWB Samples

(units % by weight of solder on the boards)

Board Type	Sn-Pb	Sn-Ag-Bi	Sn-Ag-Cu	Sn-Ag-Bi-Cu	Sn-Cu
A	1.7%	1.8%	1.5%	1.5%	1.5%
B	0.66%	0.68%	0.58%	0.58%	0.58%
C	5.9%	6.4%	5.3%	5.6%	5.3%
D	1.0%	1.0%	0.87%	0.88%	0.87%

Notes:

- Board types A, B, and D were determined by acid digestion of a sample from the Sn-Ag-Bi board, followed by analysis of Bi.
- Board type C was determined by difference in weight between blank boards and populated boards.

4.0 Results

The results of the leaching tests are provided in Tables 2 – 5. Each table presents the duplicate results and the calculated mean for the TCLP and SPLP performed on each sample. In cases where one of the replicate measurements was below the detection limit and the other was not, the average was calculated by setting the non-detected sample concentration as the detection limit concentration. This provides a more conservative (higher) mean concentration. Values in the tables listed as ‘less than’ a number (e.g., <2.0) indicates the value was not detected above the detection limit.

Table 2. TCLP and SPLP Results for Sample A

Solder Type	SPLP A (mg/L)	SPLP B (mg/L)	Average SPLP (mg/L)	TCLP A (mg/L)	TCLP B (mg/L)	Average TCLP (mg/L)
63% Sn -- 37% Pb						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.76	<0.76	<0.76	<0.76	<0.76	<0.76
Cu	0.05	0.73	0.39	2.36	2.17	2.27
Pb	2.82	3.61	3.21	162	153	157
Sn	<0.02	<0.02	<0.02	<0.02	0.027	0.024
57% Bi – 42% Sn- 1% Ag						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.02	0.022	0.021	21.5	20.7	21.1
Cu	0.76	0.78	0.77	29.8	31.3	30.6
Pb	0.017	0.013	0.015	0.51	0.468	0.490
Sn	<0.02	<0.02	<0.02	0.045	<0.02	0.033
95.5% Sn – 4.0% Ag – 0.5% Cu						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.76	<0.76	<0.76	<0.76	<0.76	<0.76
Cu	1.94	1.29	1.62	29.7	28.3	29.0
Pb	<0.01	<0.01	<0.01	<0.01	0.015	0.013
Sn	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
96% Sn – 2.5% Ag –0.5% Cu – 1% Bi						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Cu	0.79	1.2	1.0	34.5	27.5	31.0
Pb	<0.01	<0.01	<0.01	<0.01	0.048	0.029
Sn	0.34	0.028	0.184	<0.02	<0.02	<0.02
99.3% Sn – 0.7% Cu						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.76	<0.76	<0.76	<0.76	<0.76	<0.76
Cu	0.94	0.73	0.84	35.7	38.4	37.0
Pb	<0.01	<0.01	<0.01	<0.01	0.026	<0.018
Sn	0.38	0.45	0.42	<0.02	<0.02	<0.02
Blank Boards						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.76	<0.76	<0.76	<0.76	<0.76	<0.76
Cu	1.01	0.81	0.91	29.2	35.8	32.5
Pb	<0.01	<0.01	<0.01	0.017	<0.01	0.014
Sn	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02

Table 3. TCLP and SPLP Results for Sample B

Solder Type	SPLP A (mg/L)	SPLP B (mg/L)	Average SPLP (mg/L)	TCLP A (mg/L)	TCLP B (mg/L)	Average TCLP (mg/L)
63% Sn -- 37% Pb						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.76	<0.76	<0.76	<0.76	<0.76	<0.76
Cu	0.07	0.06	0.065	38.9	27.7	33.3
Pb	1.78	1.59	1.68	68.1	57.7	62.9
Sn	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
57% Bi – 42% Sn- 1% Ag						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.02	<0.02	<0.02	7.54	8.99	8.27
Cu	1.03	1.01	1.02	32.8	62.1	47.5
Pb	<0.01	<0.01	<0.01	0.122	0.12	0.121
Sn	<0.02	<0.02	<0.02	0.047	<0.02	0.34
95.5% Sn – 4.0% Ag – 0.5% Cu						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.76	<0.76	<0.76	<0.76	<0.76	<0.76
Cu	1.96	1.27	1.61	49.7	50.5	50.1
Pb	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Sn	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
96% Sn – 2.5% Ag –0.5% Cu – 1% Bi						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Cu	1.31	1.36	1.34	56.3	47.0	51.7
Pb	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Sn	<0.02	0.03	0.03	<0.02	<0.02	<0.02
99.3% Sn – 0.7% Cu						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.76	<0.76	<0.76	<0.76	<0.76	<0.76
Cu	1.49	1.34	1.41	56.4	44.0	50.2
Pb	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Sn	0.068	0.033	0.051	<0.02	<0.02	<0.02
Blank Boards						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.76	<0.76	<0.76	<0.76	<0.76	<0.76
Cu	1.05	0.87	0.96	23.9	48.0	36.0
Pb	<0.01	<0.01	<0.01	0.026	<0.01	0.018
Sn	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02

Table 4. TCLP and SPLP Results for Sample C

Solder Type	SPLP A (mg/L)	SPLP B (mg/L)	Average SPLP (mg/L)	TCLP A (mg/L)	TCLP B (mg/L)	Average TCLP (mg/L)
63% Sn -- 37% Pb						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.76	<0.76	<0.76	<0.76	<0.76	<0.76
Cu	<0.02	0.11	.065	0.021	<0.02	0.021
Pb	2.33	2.66	2.50	54.5	51.4	52.9
Sn	<0.02	<0.02	<0.02	0.13	0.044	0.087
57% Bi – 42% Sn- 1% Ag						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.02	<0.02	<0.02	18.0	17.8	17.9
Cu	0.060	0.065	0.063	1.06	1.47	1.27
Pb	0.04	<0.01	0.025	0.44	0.91	0.67
Sn	<0.02	<0.02	<0.02	<0.02	.024	0.22
95.5% Sn – 4.0% Ag – 0.5% Cu						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.76	<0.76	<0.76	<0.76	<0.76	<0.76
Cu	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Pb	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Sn	<0.02	<0.02	<0.02	0.032	0.052	0.042
96% Sn – 2.5% Ag –0.5% Cu – 1% Bi						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	0.031	<0.02	0.026	<0.02	<0.02	<0.02
Cu	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Pb	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Sn	<0.02	<0.02	<0.02	<0.02	0.031	0.026
99.3% Sn – 0.7% Cu						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.76	<0.76	<0.76	<0.76	<0.76	<0.76
Cu	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Pb	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Sn	<0.02	0.036	0.028	0.14	0.088	0.114
Blank Boards						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.76	<0.76	<0.76	<0.76	<0.76	<0.76
Cu	0.068	0.054	0.061	3.13	2.07	2.60
Pb	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Sn	<0.02	0.041	0.031	<0.02	<0.02	<0.02

Table 5. TCLP and SPLP Results for Sample D

Solder Type	SPLP A (mg/L)	SPLP B (mg/L)	Average SPLP (mg/L)	TCLP A (mg/L)	TCLP B (mg/L)	Average TCLP (mg/L)
63% Sn -- 37% Pb						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.76	<0.76	<0.76	<0.76	<0.76	<0.76
Cu	0.031	0.038	0.034	0.155	0.119	0.137
Pb	2.25	2.44	2.34	18.4	16.1	17.2
Sn	<0.02	<0.02	<0.02	0.021	<0.02	0.21
57% Bi – 42% Sn- 1% Ag						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.02	<0.02	<0.02	12.3	8.21	10.3
Cu	0.503	0.021	0.262	0.444	0.361	0.387
Pb	<0.01	<0.01	<0.01	0.092	0.078	0.085
Sn	<0.02	<0.02	<0.02	0.073	<0.02	0.047
95.5% Sn – 4.0% Ag – 0.5% Cu						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.76	<0.76	<0.76	<0.76	<0.76	<0.76
Cu	<0.02	0.03	0.025	<0.02	<0.02	<0.02
Pb	0.07	<0.01	0.04	<0.01	<0.01	<0.01
Sn	<0.02	<0.02	<0.02	0.035	0.045	0.040
96% Sn – 2.5% Ag –0.5% Cu – 1% Bi						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Cu	<0.02	<0.02	<0.02	<0.02	0.039	0.03
Pb	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Sn	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
99.3% Sn – 0.7% Cu						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.76	<0.76	<0.76	<0.76	<0.76	<0.76
Cu	<0.02	<0.02	<0.02	<0.02	0.023	0.022
Pb	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Sn	<0.02	<0.02	<0.02	<0.02	0.076	0.048
Blank Boards						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.76	<0.76	<0.76	<0.76	<0.76	<0.76
Cu	<0.02	<0.02	<0.02	0.478	0.657	0.568
Pb	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Sn	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02

5.0 Observations

Several observations are noted regarding the leaching results.

- Only two of the metals in the solder types are regulated as toxicity characteristic (TC) metals and thus capable of causing the boards to be RCRA hazardous wastes: Pb and Ag. The TCLP results found lead from the SnPb board to leach at concentrations greater than the RCRA TC limit (5 mg/L). Silver did not leach to concentrations greater than its TC limit (5 mg/L), and was in fact rarely encountered above the detection limit.

- The fact that silver did not leach is contradictory to some of the limited previous research regarding silver. Most of this previous research, however, was conducted on solder alone, and not as part of a PWB. It is clear, as evidenced by the silver results, and others discussed below, that the other metals present on the PWB and in solution play a large role on the relative leachability of a given metal.

- Copper was routinely measured in all of the samples. This was a result of the copper contained in the boards themselves (with no solder). The AB board leached more copper than the C and D boards. This is likely a result of the multi-layer configuration of the AB board. More of the surface was exposed for the copper to leach. Thus, the average leachate concentration from samples C and D were used to estimate copper leaching in order to minimize the effect of copper leaching from the board itself rather than the solder.

- Copper leaching was suppressed somewhat in the tin-lead solder board. This follows expected electrochemical behavior between lead and copper.

- Lead, copper and bismuth all leached greater in the TCLP relative to the SPLP. This has been observed for lead and copper in other research. The acetic acid used as part of the TCLP acts to complex with some metals and thus increases the amount that can be leached. The marked difference between TCLP and SPLP was not noted for silver and tin; both of these metals, however, were in most cases below the detection limit.

- The Bi-Sn-Ag solder appeared to contain small levels of lead, as it was observed to leach in the TCLP for all of the board types.

- The relationship between solder density (percent solder by weight on a board) and the metal leachability was examined. Only lead and bismuth provided a clear relationship of the impact of solder density. Tin and silver were not detected routinely enough to make such comparisons. Since copper came from the boards themselves, a comparison of solder density impacts could also not be made. When comparing the leachability between samples A and B and between samples C and D, both lead and bismuth showed increased concentrations for the samples with the large solder weight. This was most evident in the TCLP results (the bismuth samples were typically below detection in the SPLP samples). While earlier drafts of this document reported a mathematical equation related the solder density to the measured leachate concentrations, such equations are omitted from this version because the relationship did not hold between the A/B samples and C/D samples. It is hypothesized that the particular configuration of the A/B samples allowed more leaching of lead and bismuth to occur per mass of solder when compared to the C/D boards. Thus, even though sample C contained more solder than sample A, sample A leached more. This could be the result of different board architecture and the fact that AB was a multi-layer board. For use in the life-cycle analysis, the average of the TCLP samples from A and B were used to estimate leaching of lead, tin, silver, and bismuth. As stated earlier, copper leachability estimates used the average of TCLP samples C and D. Samples were chosen for their greater reliability for each metal type. The measured leachate concentrations were converted to mass of metal leached per unit mass of solder using the density of the solder on the board.

- Caution should be taken when applying the TCLP results too broadly. The TCLP was designed to be a rapid test for determining whether a solid waste should be a hazardous waste because of the presence of certain toxic elements. It was designed to simulate plausible worst case leaching conditions that might be encountered in a municipal solid waste (MSW) landfill. Recent research has found that lead leachability is less in typical landfill leachate relative to the TCLP (Jang, Y.; Townsend, T. *Environ. Sci. Tech.* **2003**, *37*, 4778-4784). Other metals may actually leach more in MSW leachate. Valuable future tests would include leaching different PWBs in actual landfill leachates and to construct simulated landfills for assessing leachability in more realistic environments.

Appendix C.1. Quality Assurance Results

Quality assurance results are presented in the following tables.

Table. C.1.1. Measured concentration (mg/L) of Blank QA Samples.

	Ag Conc. (mg/L)	Cu Conc. (mg/L)	Pb Conc. (mg/L)	Sn Conc. (mg/L)	Bi Conc. (mg/L)
QA Set I	<0.02	<0.02	< 0.01	<0.01	<0.76
QA Set II	<0.02	<0.02	< 0.01	<0.01	<0.76
QA Set III	<0.02	<0.02	< 0.01	<0.01	<0.76
QA Set IV	<0.02	<0.02	< 0.01	<0.01	<0.76
QA Set V	<0.02	<0.02	< 0.01	<0.01	<0.76
QA Set VI	<0.02	<0.02	< 0.01	<0.01	<0.76

Table C.1.2. QA Recovery Results for Blank Spiked Samples

	% Ag Recovery	% Cu Recovery	% Pb Recovery	% Sn Recovery	% Bi Recovery
QA Set I	94.6%	102.6%	103.6 %	108.3 %	107%
QA Set II	93%	94.6 %	101.2 %	105.7 %	115.7 %
QA Set III	106.1%	91.7 %	95.5 %	96.7 %	109.6 %
QA Set IV	114.1%	88.8 %	94%	92.4 %	110.3 %
QA Set V	96.9%	93.7%	100.2 %	94.8 %	99.7 %
QA Set VI	93.7%	94.7 %	98.2%	102.3 %	115.4%

Table C.1.3. QA Recovery Results for Blank Spiked Samples.

	% Ag Recovery	% Cu Recovery	% Pb Recovery	% Sn Recovery	% Bi Recovery*
QA Set I	96.5%	91.3%	98.4%	88.1%	104.2%
QA Set II	101.2%	91.5%	94.8%	97.9%	96.5%
QA Set III	81.2%	96.8%	98.2%	100.3%	87.2%
QA Set IV	94.2%	118.6%	96.6%	106.2%	95.5%
QA Set V	108.1%	93.6%	97.7%	106.8%	
QA Set VI	89.2%	93.7%	97.5%	103.4%	

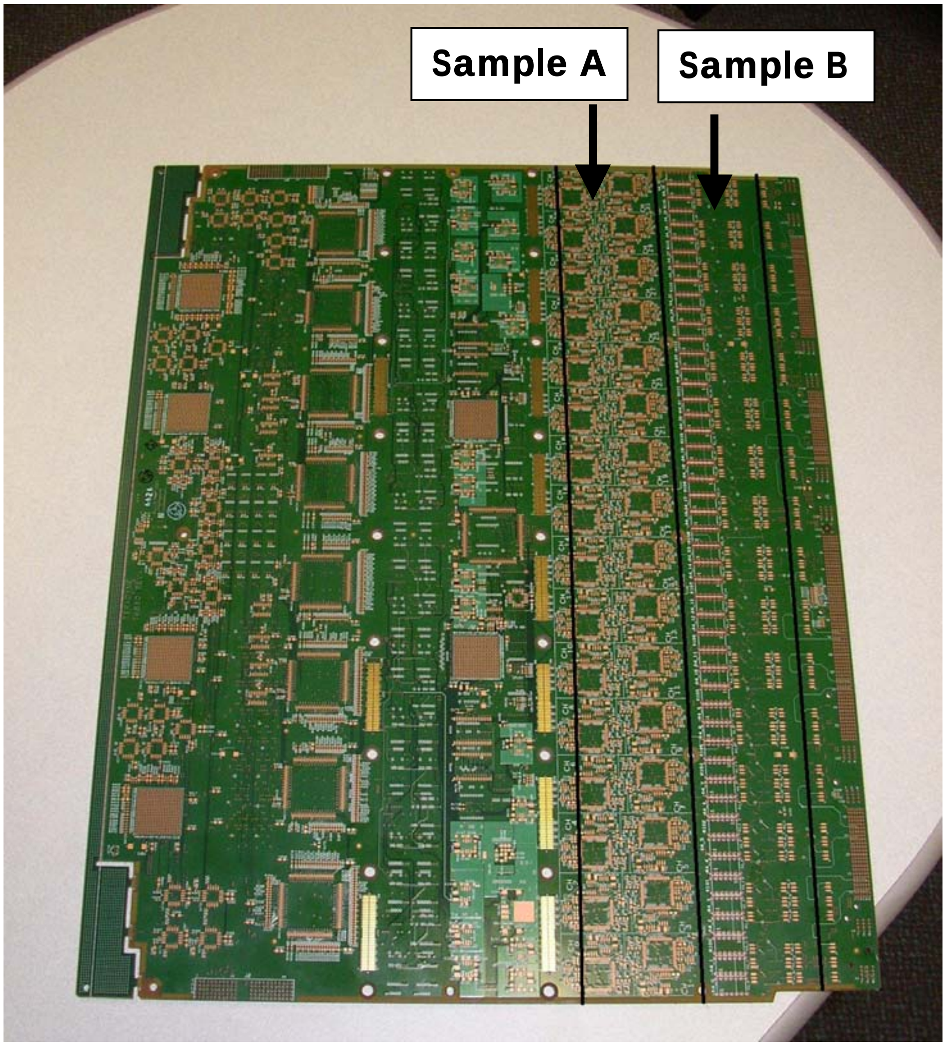
* Only four QA data points were needed for Bi analysis because of the limited sample set number analyzed.

Table C.1.4. Mean concentrations for all TCLP and SPLP Reagent Blank samples.

	Ag Conc. (mg/L)	Cu Conc. (mg/L)	Pb Conc. (mg/L)	Sn Conc. (mg/L)	Bi Conc. (mg/L)
TCLP Blanks	<0.02	<0.02	<0.01	<0.02	< 0.76
SPLP Blanks	<0.02	<0.02	<0.01	<0.02	< 0.76

Appendix C.2 Location of Sample on Board AB

Board AB consisted on one large multi-layer board. Two approximately 100-g areas were identified and cut from each board sample for leach testing. To minimize the number of cuts performed, two side-by-side locations were selected in long strips. The following figure illustrates the approximate location of these two samples, identified as A and B. The A sample visually contained a greater density of solder than the B sample.



APPENDIX D:
LIFE-CYCLE IMPACT ASSESSMENT SUPPORT DATA (NON-TOXICITY)

Global warming potentials

Flow	Global warming potentials (100-year CO_2-equivalents)	Sources			
CF3I	<1			c	
Carbon dioxide [Inorganic emissions to air]	1	a	b	c	d
Ch2Br2	1			c	
Ch3Br	5			c	
Dichloromethane (methylene chloride) [Halogenated organic emissions to air]	10	a		c	
HFC-161 CH_3CH_2F	12	a			
CH3Cl	16			c	
Methane [Organic emissions to air (group VOC)]	23	a			
Trichloromethane (chloroform) [Halogenated organic emissions to air]	30	a			
HFC-152 CH_2FCH_2F	43	a		c	
HFC-41 Methyl fluoride 593-53-3	97	a			
HCFC 123 (dichlorotrifluoroethane) [Halogenated organic emissions to air]	120	a		c	
HFC 152a (difluoroethane) [Halogenated organic emissions to air]	120	a			
Trichloroethane [Halogenated organic emissions to air]	140	a		c	
HCFC 225ca (dichloropentafluoropropane) [Halogenated organic emissions to air]	180	a		c	
HCFC-21 CHCl2F	210			c	
Nitrous oxide (laughing gas) [Inorganic emissions to air]	296	a			
HFC 143 (trifluoroethane) [Halogenated organic emissions to air]	330	a			
ChBrF2	470			c	
HFC-32 Difluoromethane 75-10-5	550	a			
HCFC 124 (chlorotetrafluoroethane) [Halogenated organic emissions to air]	620	a		c	
HCFC 225cb (dichloropentafluoropentane) [Halogenated organic emissions to air]	620	a		c	
HFC 245ca (pentafluoropropane) [Halogenated organic emissions to air]	640	a			
HCFC 141b (dichloro-1-fluoroethane) [Halogenated organic emissions to air]	700	a		c	
HFC-365mfc $CF_3CH_2CF_2CH_3$	890	a			
HFC-245fa $CHF_2CH_2CF_3$	950	a			
HFC-134 1,1,2,2-tetrafluoro-1,2-diiodoethane 359-35-3	1100	a			
HFC-236ea CHF_2CHFCF_2	1200	a			
HFC 134a (tetrafluoroethane) [Halogenated organic emissions to air] '	1300	a			d
HFC-236cb $CH_2FCF_2CF_3$	1300	a			
Halon (1211)	1300			c	
HFC 43-10 (decafluoropentane) [Halogenated organic emissions to air]	1500	a			
CFC (soft)	1600		b		
HCFC 22 (chlorodifluoromethane) [Halogenated organic emissions to air]	1700	a			d*
Carbon tetrachloride (tetrachloromethane) [Halogenated organic emissions to air]	1800	a			
HCFC 142b (chlorodifluoroethane) [Halogenated organic emissions to air]	2400	a			
HFC 125 (pentafluoroethane) [Halogenated organic emissions to air]	3400	a	b		
HFC 227ea (heptafluoropropane) [Halogenated organic emissions to air]	3500	a			
HFC 143a (trifluoroethane) [Halogenated organic emissions to air]	4300	a			
CFC 11 (trichlorofluoromethane) [Halogenated organic emissions to air]	4600	a			
Tetrafluoromethane [Halogenated organic emissions to air]	5700	a		c	
CFC 113 (trichlorofluoroethane) [Halogenated organic emissions to air]	6000	a		c	
Halon (1301) [Halogenated organic emissions to air]	6900	a		c	

Flow	Global warming potentials (100-year CO_2-equivalents)	Sources			
CFC (hard)	7100		b		
CFC 115 (chloropentafluoroethane) [Halogenated organic emissions to air]	7200	a			
Octafluoropropane perfluoropropane 76-19-7	8600	a		c	
Decafluorobutane perfluorobutane 355-25-9	8600	a		c	
Cyclooctafluorobutane perfluorocyclobutane 115-25-3	8700				d
Dodecafluoro-pentane perfluoropentane 678-26-2	8900	a		c	
Tetradecafluorhexane perfluorohexane 355-42-0	9000	a		c	
HFC 236fa (hexafluoropropane) [Halogenated organic emissions to air]	9400	a		c	
CFC 114 (dichlorotetrafluoroethane) [Halogenated organic emissions to air]	9800	a		c	
CFC 12 (dichlorodifluoromethane) [Halogenated organic emissions to air]	10600	a		c	
CFC 116 (hexafluoroethane) [Halogenated organic emissions to air]	11900	a			
HFC 23 (trifluoromethane) [Halogenated organic emissions to air]	12000	a			
CFC 13 (chlorotrifluoromethane) [Halogenated organic emissions to air]	14000	a		c	
Sulphur hexafluoride [Inorganic emissions to air]	22200	a		c	

Sources:
(a) IPPC 2001 Report: IPCC - Albritton, D.L. ; Meiro Filho, L.G.. www.ipcc.ch/pub/wg1TARtechsum.pdf.
(b) Eco-Indicator 1995.
(c) WMO 98 report: The Scientific Assessment of Ozone Depletion,1998. World Meteorological Organisation, Global Ozone Research and Monitoring Project. Report No. 44. 100 year.
(d) LCA Handbook: Houghton et al., 1994 & 1996; GWP values for the substances marked with * are 1994.

Ozone depletion potentials

Flow	Ozone depletion potential (ODP) (CFC-11 equivalents)	Sources					
HCFC- 151 C2H4FCl	0.005	a*					
HCFC-251 C3H4FCl3	0.01	a*					
HCFC-123	0.02	a' *		c			
Methyl Chloride	0.02		b		d		
HCFC-31 CH2FCL	0.02	a*					
HCFC-261 C3H5FCl2	0.02	a*					
HCFC-262 C3H5F2Cl	0.02	a*					
HCFC-124	0.022	a' *		c			
HCFC-225ca	0.025	a' *		c			
HCFC-253 C3H4F3Cl	0.03	a*					
HCFC-271 C3H6FCl	0.03	a*					
HCFC-225cb	0.033	a' *		c			
HCFC-21 CHFCl2	0.04	a' *					
HCFC-121 C2HFCl4	0.04	a*					
HCFC-252 C3H4F2Cl2	0.04	a*					
HCFC-131 C2H2FCl3	0.05	a*					
HCFC-132 C2H2F2Cl2	0.05	a*					
HCFC 22 (chlorodifluoromethane)	0.055	a*		c			
CFC (soft)	0.055			c			
HCFC-133 C2H2F3Cl	0.06	a*					
HCFC 142b (chlorodifluoroethane)	0.065	a*		c		e	
HCFC-141 C2H3FCl2	0.07	a*					
HCFC-142 C2H3F2Cl	0.07	a*					
HCFC - 221 C3HFCl6	0.07	a*					
HCFC-225 C3HF5Cl2	0.07	a*					
HCFC-122 C2HF2Cl3	0.08	a*					
HCFC-223 C3HF3Cl4	0.08	a*					
HCFC-222 C3HF2Cl5	0.09	a*					
HCFC-224 C3HF4Cl3	0.09	a*					
HCFC-231 C3H2FCl5	0.09	a*					
HCFC-241 C3H3FCl3	0.09	a*					
Trichloroethane [Halogenated organic emissions to air]	0.1	a**					
HCFC-226 C3HF6Cl	0.1	a*					
HCFC-232 C3H2F2Cl4	0.1	a*					
C2H4FBr	0.1	a*					
HCFC 141b (dichloro-1-fluoroethane) [Halogenated organic emissions to air]	0.11	a*		c			
HCFC-243 C3H3F3Cl2	0.12	a*					
HCFC-242 C3H3F2Cl3	0.13	a*					
Halon-2311	0.14			c	d		
HBFC-2311	0.14		b*				
HCFC-244 C3H3F4Cl	0.14	a*					
HCFC-233 C3H2F3Cl3	0.23	a*					
Halon-2401	0.25			c	d		
HBFC-2401	0.25						
HCFC- 234 C3H2F4Cl2	0.28	a*					

Flow	Ozone depletion potential (ODP) (CFC-11 equivalents)	Sources					
C3H4FBr3	0.3	a*					
C3H5FBr2	0.4	a					
HCFC-235 C3H2F5Cl	0.52	a*					
air]	0.6	a"				e	
Methyl bromide [Halogenated organic emissions to air]	0.6	a		c			
C3H6FBr	0.7	a*					
CH2FBr	0.73	a*					
CHF2Br HBFC-22B1; bromodifluoromethane	0.74	a"					
CFC 113 (trichlorofluoroethane) [Halogenated organic emissions to air]	0.8	a"				e	
C2HFBr4	0.8	a*					
C3H4F3Br	0.8	a*					
C3H5F2Br	0.8	a*					
CFC 114 (dichlorotetrafluoroethane) [Halogenated organic emissions to	1	a"				e	
CFC 13 (chlorotrifluoromethane) [Halogenated organic emissions to air]	1	a				e	
CFC 12 (dichlorodifluoromethane) [Halogenated organic emissions to air]	1	a"		c		e	
CFC 11 (trichlorofluoromethane) [Halogenated organic emissions to air]	1	a"	b	c	d	e	f
CFC-111 pentachlorofluoroethane	1	a					
CFC- 112 Tetrachlorodifluoroethane	1	a					
CFC-211 heptachlorofluoropropane	1	a					
CFC-212 hexachlorotrifluoropropane	1	a					
CFC-213 pentachlorotrifluoropropane	1	a					
CFC-214 Tetrachlorotetrafluoropropane	1	a					
CFC-215 trichloropentafluoropropane	1	a					
CFC-216 dichlorohexafluoropropane	1	a					
CFC-217 monochloroheptafluoropropane	1	a					
CFC (hard)	1			c			
CHFBr2	1	a*					
C3H4F2Br2	1	a*					
Carbon tetrachloride (tetrachloromethane) [Halogenated organic emissions to air]	1.1	a				e	
C2H2FBr3	1.1	a*					
C2H3F2Br	1.1	a*					
C2HF4Br	1.2	a*					
Halon- 1202	1.25		b*	c	d		
Halon-1201	1.4			c	d		
HBFC-1201	1.4		b*				
C2H2F2Br2	1.5	a*					
C3HFBr6	1.5	a*					
C2HF3Br2	1.6	a*					
C2H2F3Br	1.6	a*					
C2H3FBr2	1.7	a*					
C2HF2Br3	1.8	a*					
C3HF3Br4	1.8	a*					
C3HF2Br5	1.9	a*					
C3H2FBr5	1.9	a*					
C3H3FBr4	1.9	a*					

Flow	Ozone depletion potential (ODP) (CFC-11 equivalents)	Sources					
C3HF5Br2	2	a*					
C3H2F2Br4	2.1	a*					
C3HF4Br3	2.2	a*					
C3H3F3Br2	2.5	a*					
Halon (1211) [Halogenated organic emissions to air]	3	a"				e	
C3H3F2Br3	3.1	a*					
C3HF6Br	3.3	a*					
C3H3F4Br	4.4	a*					
C3H2F3Br3	5.6	a*					
Halon (2404) [Halogenated organic emissions to air]	6					e	
Halon 2402 dibromotetrafluoroethane 124-73-2	6	a*					
C3H2F4Br2	7.5	a*					
Halon (1301) [Halogenated organic emissions to air]	10	a"				e	
C3H2F5Br	14	a*					

Sources:

(a) Montreal Protocol / UNEP (www.uneptie.org/ozonaction/compliance/protocol/ods.html).

a" These values are estimates and will be revised periodically.

a** This formula does not refer to 1,1,2-trichloroethane.

a' Identifies the most commercially viable substances with ODP values listed against them to be used for the purposes of the Protocol.

a* Where a range of ODPs is indicated, the highest value in that range shall be used for the purposes of the Protocol.

(b) WMO (World Meteorological Organisation), 1999. *Scientific Assessment of Ozone Depletion: 1998.* Global Ozone Research and Monitoring project - Report no. 44. Geneva. in Guinee, 2002: LCA Handbook, Institute of Environmental Sciences, The Netherlands.

b* WMO (World Meteorological Organisation), 1992. Scientific Assessment of Ozone Depletion: 1991. Global Ozone Research and Monitoring Project - Report no. 25. Geneva. in Guinee, 2002: LCA Handbook, Institute of Environmental Sciences, The Netherlands.

Solomon, S. and Wuebbles, D.J. (1995) Ozone Depletion Potentials, Global Warming Potentials and Future Chlorine/Bromine Loading, in Scientific Assessment of Ozone Depletion: 1994 (Assessment Co-Chairs D.L. Albritton, R.T. Watson and P.J. Aucamp), World Meteorological Organisation, Global Ozone Research and Monitoring Project, Report No. 37, World Meteorological Organisation, Geneva.

(c) Heijungs et al. (1992) and The Eco-Indicator -Final Report. NOH. 1995.

(d) Hauschild 1998 and Eco-Indicator 1999.

(e) The Scientific Assessment of Ozone Depletion,1998. World Meteorological Organisation, Global Ozone Research and Monitoring Project. Report No. 44. In GaBi3 (GaBi, 2000).

(f) Solomon, S. and Albritton, D.L. (1992) Time-Dependent Ozone Depletion Potentials for Short and Long-Term Forecasts. *Nature,* **357,** 33-37. In Wenzel and Hauschild, 1995.

Photochemical oxidant potential

Flow	Photochemical oxidant potential	Sources					
Chloromethane (methyl chloride) [Halogenated organic emissions to air]	0.005	a					
Methane [Organic emissions to air (group VOC)] *(alkane)*	0.006	a	b				
Trichloroethane [Halogenated organic emissions to air] (Methyl chloroform)	0.021			c			
Carbon tetrachloride (tetrachloromethane) [Halogenated organic emissions to air]	0.021			c			
Polychlorinated dibenzo-p-dioxins (2,3,7,8 - TCDD) [Halogenated organic emissions to air]	0.021						f
Polychlorinated dibenzo-p-furans (2,3,7,8 - TCDD) [Halogenated organic emissions to air]	0.021						f
Dichloroethane (isomers) [Group NMVOC to air]	0.021			c			f
Tetrafluoromethane [Halogenated organic emissions to air]	0.021						f
air]	0.021						f
Dichlorobenzene (p-DCB; 1,4-dichlorobenzene) [Halogenated organic emissions to air]	0.021						f
Chlorobenzene [Halogenated organic emissions to air]	0.021						f
CFC 113 (trichlorofluoroethane) [Halogenated organic emissions to air]	0.021						f
Vinyl chloride (VCM; chloroethene) [Halogenated organic emissions to air]	0.021			c			f
air]	0.021						f
Polychlorinated biphenyls (PCB unspecified) [Halogenated organic emissions to air]	0.021						f
CFC 22 (chlorodifluoromethane) [Halogenated organic emissions to air]	0.021						f
air]	0.021						f
CFC 142b (chlorodifluoroethane) [Halogenated organic emissions to air]	0.021						f
CFC 134a (tetrafluoroethane) [Halogenated organic emissions to air]	0.021						f
CFC 13 (chlorotrifluoromethane) [Halogenated organic emissions to air]	0.021						f
CFC 125 (pentafluoroethane) [Halogenated organic emissions to air]	0.021						f
CFC 12 (dichlorodifluoromethane) [Halogenated organic emissions to air]	0.021						f
Dichlorobenzene (o-DCB; 1,2-dichlorobenzene) [Halogenated organic emissions to air]	0.021						f
CFC 116 (hexafluoroethane) [Halogenated organic emissions to air]	0.021						f
air]	0.021						f
CFC 11 (trichlorofluoromethane) [Halogenated organic emissions to air]	0.021						f
CxHy Chloro	0.021			c			
Trichloromethane (chloroform) [Halogenated organic emissions to air]	0.023	a					
dimethyl carbonate	0.025	a*					
Methyl Formate	0.027	a*					
Nitrogen Dioxide	0.028	a**					
Tetrachloroethene (perchloroethylene) [Halogenated organic emissions to air] (tetrachloroethylene)	0.029	a					
Formic acid	0.032	a					
Carbon monoxide [Inorganic emissions to air]	0.036						f
Sulphur Dioxide	0.048	a*					
Tertiary - Butyl Acetate	0.053	a*					
Methyl acetate [Group NMVOC to air] (esters)	0.059	a*					

Flow	Photochemical oxidant potential	Sources					
Dichloromethane (methylene chloride) [Halogenated organic emissions to air]	0.068	a					
Ethene (acetylene) [Group NMVOC to air] *(alkyne)*	0.085		b				
Tertiary Butanol	0.106	a*					
Ethane [Group NMVOC to air] *(alkane)*	0.123	a	b	c			
Methanol [Group NMVOC to air] *(alcohol)*	0.14	a*					
Styrene [Group NMVOC to air]	0.142	a					
2-methyl 2-butanol	0.142		b				
Propionic acid (79-09-4)	0.15	a					
Dimethoxy methane (Methylal)	0.164	a*					
Neopentane (dimethylpropane)	0.173	a	b				
Methyl tert-Butyl Ether	0.175	a*					
Propane [Group NMVOC to air]*(alkanes)*	0.176	a	b				
Acetone (dimethylcetone) [Group NMVOC to air] (*ketone)*	0.178			c			f
Propanol (iso-propanol; isopropanol) [Group NMVOC to air]	0.188	a*					
Benzene [Group NMVOC to air] (*Aromatic)*	0.189			c			f
Dimethyl Ether	0.189	a*					
Furfuryl alcohol [Group NMVOC to air]	0.196						f
Butylene glycol (butane diol) [Group NMVOC to air]	0.196						f
Alcohols	0.196			c			
Methyl Ether Acetate	0.2				d		
Ethylene acetate (ethyl acetate) [Group NMVOC to air]	0.209	a*					
Isopropyl acetate *(Esters)*	0.211	a*					
Propyl acetate [Group NMVOC to air]	0.215						f
Vinyl acetate	0.223			c			
2,2- dimethylbutane *(alkanes)*	0.241		b				
Ethyl- trans-Butyl Ether	0.244	a*					
sec-Butyl Acetate	0.275	a*					
Cyclohexanone [Group NMVOC to air]	0.299	a	b				
Butan-2-diol (look at item 44)	0.3				d	e	
Isobutane CH(CH3)3 *(alkanes)*	0.307	a	b				
Diacetone alcohol	0.307	a*					
Butylacetate [Group NMVOC to air]	0.323						f
Methyl tert-butylketone (Pinacolin)	0.323	a	b				
Trichloroethene (isomers) [Halogenated organic emissions to air] (trichloroethylene)	0.325	a					
Ketones	0.326			c			
VOC (unspecified) [Organic emissions to air (group VOC)]	0.337						f
n-dodecane *(alkanes)*	0.357	a	b				
Isobutanol (*alcohol)*	0.36	a*					
3-methylhexane *(alkanes)*	0.364		b				
Methyl Isopropyl Ketone	0.364	a	b				
3-methyl 2-butanol	0.366		b				
Ethylene glycol	0.373	a*					
Methyl ethyl ketone	0.373		b				
Terpentine	0.377			c			
Ethylene Oxide	0.377			c			
Hydroxy compounds *Item 67*	0.377			c			

Flow	Photochemical oxidant potential	Sources					
Methyl mercaptan	0.377			c			
Ethane diol	0.382		b				
n-decane *(alkanes)*	0.384		b				
n-undecane *(alkanes)*	0.384		b				
Decane	0.384	a					
Dichloroethene (trans)	0.392	a					
Pentane (n-pentane) [Group NMVOC to air] (*alkanes)*	0.395	a	b				
Crude Oil	0.398			c			
CxHy Hydrocarbons	0.398			c			
Petrol	0.398			c			
Diisopropyl ether	0.398	a*					
Ethanol (ethyl alcohol) [Group NMVOC to air] *(alcohol)*	0.399	a*					
2-methylnonane *(alkanes)*	0.4				d	e	
Butanol *(alcohol)*	0.4					e	
Isobutyl Acetate	0.4				d		
isopentane CH2CH(CH3)C2H5 *(alkanes)*	0.405	a	b				
2-methyl 1-butanol	0.407		b				
Butane (n-butane) [Group NMVOC to air]*(alkanes)*	0.41						f
2-methylhexane *(alkanes)*	0.411		b				
3-methyl 1-butanol	0.412		b				
n-nonane *(alkanes)*	0.414	a	b				
Diethyl Ketone	0.414	a					
3-pentanone	0.414		b				
NMVOC (unspecified) [Group NMVOC to air]	0.416			c			f
2-methylpentane *(alkanes)*	0.42		b				
3-pentanol	0.422		b				
Nitrogen mono oxide	0.427	a					
Aldehydes	0.443			c			
Diethyl Ether	0.445	a*					
sec-Butanol	0.447	a*					
Octane	0.453	a					
Propylene glycol [Group NMVOC to air]	0.457	a*					
Propane diol	0.457		b				
3-methylpentane *(alkanes)*	0.479		b				
Hexane (isomers) [Group NMVOC to air] (alkanes)	0.482	a	b				
Methyl Isobutyl ketone (hexone) (*ketone)*	0.49	a	b				
Octane [Group NMVOC to air] *(alkanes)*	0.493						f
Heptane (isomers) [Group NMVOC to air] *(alkane)*	0.494	a	b				
2-methylheptane *(alkanes)*	0.5				d	e	
2-methyloctane *(alkanes)*	0.5				d	e	
Isopropylbenzene *(aromatic)*	0.5		b		d		
Methyl ether	0.5				d	e	
Isopropyl benzene (cumene)	0.5	a					
Isobutyraldehyde (iso-butanal) separate in Source a	0.514	a	b				
Cyclohexanol [Group NMVOC to air]	0.518	a*					
Formaldehyde (methanal) [Group NMVOC to air] *(aldehydes)*	0.519	a	b				
Ethanal (Acetaldehyde) [Group NMVOC to air]	0.52701						f
2,3- dimethylbutane *(alkanes)*	0.541		b				

Flow	Photochemical oxidant potential	Sources					
n-Propanol	0.543		b				
2-pentanone	0.548		b				
Methyl propyl Ketone	0.548	a					
Butyraldehyde (n-; iso-butanal) [Group NMVOC to air]	0.568						f
Hexa-2-one	0.572	a	b				
Hexa-3-one	0.599	a	b				
Methylcyclohexane *(alkanes)*	0.6					e	
n-butanol	0.612		b				
Isobutene *(alkene) isobutylene*	0.627	a					
Methyl propene	0.627		b				
n-propylbenzene *(aromatic)*	0.636		b				
Toluene (methyl benzene) [Group NMVOC to air] *(aromatic)*	0.637	a	b				
Acetaldehyde (*aldehyde)*	0.641		b				
3-methylbut-1-ene (*alkene)*	0.671		b				
Allyl chloride	0.7					e	
Ethyl benzene [Group NMVOC to air] *(aromatic)*	0.73	a	b				
Polycyclic aromatic hydrocarbons (PAH) [Group PAH to air]	0.76098						f
Benzo{a}pyrene [Group PAH to air]	0.761						f
Cyclohexane (hexahydro benzene) [Group NMVOC to air]	0.761						f
Phenol (hydroxy benzene) [Group NMVOC to air]	0.761			c			f
Cyclopentanone [Group NMVOC to air]	0.761						f
Caprolactam	0.761			c			
Chlorophenols	0.761			c			
CxHy Aromatic	0.761			c			
Diphenyl	0.761			c			
Hexachlorobiphenyl	0.761			c			
Naphthalene	0.761			c			
Phthalic acid anhydride	0.761			c			
Valeraldehyde (*aldehyde) (p*entanaldehyde)	0.765	a					
Pentanal	0.765		b				
2-methylbut-1-ene *(alkene)*	0.771		b				
Xylene (dimethyl benzene) [Group NMVOC to air]	0.777						f
Propionaldehyde Propanol (aldehyde)	0.798	a	b				
Acrolein *(aldehyde)*	0.8				d	e	
2-methylbut-2-ene (*alkene)*	0.842		b				
1,3 - butadiene (look at 74)	0.851		b				
1-hexene	0.874		b				
o-ethyltoluene *(aromatic)* (2-ethyltoluene)	0.898	a	b				
Butadiene [Group NMVOC to air]	0.906						f
p-ethyltoluene *(aromatic)* (4-ethyltoluene)	0.906	a	b				
Butene (vinyl acetylene) [Group NMVOC to air]	0.959						f
1-pentene *(alkene)*	0.977		b				
Ethene (ethylene) [Group NMVOC to air]*(alkenes)*	1	a	b	c	d	e	f
p-xylene (*aromatic)*	1.01	a	b				
m-ethyltoluene *(aromatic)* (3-ethyltoluene)	1.02	a	b				
o-xylene (*Aromatic)*	1.05	a	b				
Trans-2-hexene	1.07	a	b				
cis 2-hexene	1.07		b				

Flow	Photochemical oxidant potential	Sources					
1-butene *(alkene)*	1.08		b				
Isoprene *(alkene)*	1.09	a	b				
1,2,5-trimethylbenzene *(aromatic)*	1.1					e	
m-xylene (*aromatic)*	1.11	a	b				
Propene (propylene) [Group NMVOC to air]*(alkene)*	1.12	a	b				
2-pentene (trans) *(alkene)*	1.12	a	b				
cis 2-penene	1.12		b				
2-butene (trans) *(alkene)*	1.13	a	b				
cis 2-butene	1.15		b				
1,2,3- Trimethylbenzene *(aromatic)*	1.27		b				
1,2,4- trimethylbenzene *(aromatic)*	1.28		b				
3,5 dimethyl toluene	1.3		b				
3,5 dimethyl ethyl benzene	1.32		b				
1,3,5 - trimethyl benzene	1.38		b				

Sources:

(a) LCA Handbook: Derwent, R.G., M.E. Jenkin, S.M. Saunders & M.J. Piling, 1998. *Photochemical Ozone Creation Potentials for Organic Compounds in Northwest Europe Calculated with a Master Chemical Mechanism. Atmos. Environ. 32 (14-15): 2429-2441.*

* updated from Jenkin, M.E. & G.D. Hayman, 1999. *Photochemical Ozone Creation Potentials for Oxygenated Volatile Organic Compounds: Sensitivity to Variations in Kinetic and Mechanistic Parameters.*

** value for inorganic substances from Derwent, R.G., M.E. Jenkin & S.M. Saunders, 1996. *Photochemical Ozone Creation Potentials for a Large Number of Reactive Hydrocarbons under European Conditions. Atmos.*

(b) Eco-Indicator 1999.

(c) Eco-Indicator 1995. j ( )

Photochemical Ozone Creation Potentials: A Study of Different Concepts. J. Air Waste Manage. Assoc. 42(9), 1152-1158.

(e) High NO x: Wenzel and Hauschild: Anderson- Skold, Y., Grennfelt, P. and Pleijel, K. (1992) Photochemical Ozone Creation Potentials: A Study of Different Concepts. J. Air Waste Manage. Assoc. 42(9),

(f) GaBi3 (PE & IKP, 2000).

Acidification potentials

Flow	Acidification potential ($S0_2$-equivalents)	Sources			
Tetrachloroethene (perchloroethylene) [Halogenated organic emissions to air]	0.19		b		
Hydrogen bromine (hydrobromic acid) [Inorganic emissions to air]	0.396		b		
Nitric acid [Inorganic emissions to air]	0.508		b		
Chloromethane (methyl chloride) [Halogenated organic emissions to air]	0.634		b		
Vinyl chloride (VCM; chloroethene) [Halogenated organic emissions to air]	0.634		b		
Sulphuric acid [Inorganic emissions to air]	0.653		b		
Nitrogen Dioxides	0.7	a		c	d
Nitrogen oxides [Inorganic emissions to air] (NOx)	0.7	a	b	c	d
Trichloroethane [Halogenated organic emissions to air]	0.72		b		
Trichloroethene (isomers) [Halogenated organic emissions to air]	0.72		b		
Dichloromethane (methylene chloride) [Halogenated organic emissions to air]	0.744		b		
Sulfur Trioxide	0.8	a		c	
Trichloromethane (chloroform) [Halogenated organic emissions to air]	0.803		b		
Carbon tetrachloride (tetrachloromethane) [Halogenated organic emissions to ai	0.83		b		
Hydrochloric Acid	0.88			c	d
Hydrogen chloride [Inorganic emissions to air]	0.88	a	b		
Phosphoric Acid	0.98	a		c	
Sulfur Oxides	1				d
Sulphur dioxide [Inorganic emissions to air]	1	a	b	c	d
Nitric Oxide	1.07			c	d
Nitrogen monoxide	1.07	a			
Hydrogen cyanide (prussic acid) [Inorganic emissions to air]	1.185		b		
Hydrofluoric acid	1.6			c	d
Hydrogen fluoride [Inorganic emissions to air]	1.6	a	b		
Ammonia [Inorganic emissions to air]	1.88	a	b	c	d
Hydrogen sulphide [Inorganic emissions to air]	1.88		b	c	

Sources:

(a) LCA Handbook: Heijungs, R., J.B. Guinee, G. Huppes, R.M. Lankreijer, H.A. Udo de Haes, A. Wegener Sleeswijk, A.M.M. Ansems, P.G. Eggels, R. van Duin, and H.P. de Goede. 1992. Environmental Life-Cycle Assesment of Products. Vol. I: Guide, and Vol II: Backgrounds. Leiden: CML Center for Environmental Studies, Leiden University.

(b) GaBi3 (PE & IKP, 2000).

(c) Hauschild and Wenzel - Hauschilld, M.Z. and Wenzel, H. Acidification as Assessment Criterion in the Environmental Assessment of Products, in: *Scientific Background for Environmental Assessment of Products* (eds M. Hauschild and H. Wenzel), Chapman & Hall, London. 1997.

(d) Eco-Indicator 1995.

Eutrophication potentials of material flows to water

Flow	Eutrophication potential (phosphate-equivalents)	Sources	
Chemical oxygen demand (COD) [Analytical measures to water]	0.022	a	b
Nitrate [Inorganic emissions to water]	0.1	a	b
Nitric Acid	0.1	a	
Nitrogen dioxide	0.13	a	
Nitrogen Monoxide	0.2	a	
Ammonium [Inorganic emissions to water]	0.33	a	b
Ammonia [Inorganic emissions to water]	0.35	a	
Total Nitrogen	0.42	a	
Phosphoric acid	0.97	a	
Phosphate [Inorganic emissions to water]	1	a	b
Phosphorous oxide	1.34	a	
Total Phosphorus	3.06	a	

Sources:
(a) LCA Handbook (2001): Based on Heijungs et al. (1992) with some modifications.
(b) GaBi3 (PE & IKP 2000).

APPENDIX E:
LIFE-CYCLE IMPACT ASSESSMENT
SUPPORT DATA (TOXICITY)

APPENDIX E:

SUPPORTING TOXICITY DATA

E.1 TOXICITY DATA COLLECTION

Background:

In the Lead Free Solder Project (LFSP), human and ecological toxicity impacts are calculated by using a chemical ranking method (described in Chapter 3, Sections 3.2.11 through 3.2.13). This method was originally developed for a life-cycle assessment (LCA) done with support from the EPA Office of Research and Development (ORD) and Saturn Corporation. It was updated for the EPA's Design for the Environment (DfE) Program Computer Display Project (CDP) in consultation with ORD. The final CDP method was reviewed by ORD as well as EPA's Office of Pollution Prevention and Toxics Risk Assessment Division (RAD) prior to publication (Socolof et al., 2001). Other minor updates have been made for this LFSP, which include (1) separating chronic heath impacts into cancer impacts and chronic non-cancer impacts (for both public and occupational impacts) and (2) removing the presentation of the terrestrial ecotoxicity impact category.

Separating the chronic human impacts into two separate categories was done because the hazard values (HVs) calculated for each of these two impact categories are calculated based on geometric means for different endpoints. For cancer impacts, the HV is based on the geometric mean of cancer slope factors. The geometric mean for cancer slope factors are largely influenced by the slope factors for dioxins, which are very high. Thus the associated hazard values of most cancer impacts have numerically small HVs (since the HV is calculated by dividing the chemical-specific slope factor by the geometric mean). Compared to the non-cancer HVs, the cancer HVs are generally much smaller numbers. Therefore, combining the two impact scores into one impact category causes the non-cancer impacts to overshadow the cancer impacts. Therefore, to observe any real resolution in the cancer impact category, the cancer and non-cancer impact categories have been separated for the LFSP.

The other change from the CDP was to remove the terrestrial toxicity impact category as being presented independently, because the chronic non-cancer impacts presented alone are calculated the same way as the terrestrial ecotoxicity impacts. Thus, the terrestrial ecotoxicity impacts are represented by the non-cancer impacts and thus are not presented separately in the LFSP.

In the LCA, there is no intent to conduct a full risk assessment or even a screening level risk assessment, given that there are no real spatial or temporal boundaries to this global, industry-wide LCA. In order to provide some weighting of the inventory data to represent potential toxicity, basic toxicity data (e.g., a no observable adverse effect level [NOAEL] for chronic, non-carcinogenic effects) are used. The intent is to modify the inventory data by the inherent toxicity of the material to provide a relative toxicity measure.

Table E-1 lists the toxicity data used for potentially toxic chemicals in the LFSP inventory, and Table E-2 lists the associated HVs calculated per the methodologies described in Section 3.2.11 through 3.2.13. To save project resources, toxicity data that had been collected for previous DfE projects were used in the LFSP. Toxicity data used prior to this project were collected by Syracuse Research Corporation (SRC) (under contract with EPA) and EPA's RAD. Chemicals identified in the LFSP inventory, for which toxicity data had not been previously collected, were collected by the Toxicity and Hazard Assessment Group in the Life Sciences Division at the Oak Ridge National Laboratory (ORNL). ORNL conducted their search in April, 2003, and the data were subsequently reviewed and/or supplemented by EPA's RAD. The description below presents the method used to collect the LFSP toxicity data.

Data Collection Approach:

Once inventory data are collected for the project, the inventory flows are checked to determine if they are potentially toxic. The lists of potentially toxic and non-toxic chemicals were reviewed by EPA. Those excluded from the toxicity list, and assumed to be non-toxic are provided in Table E-3. The chemicals then deemed potentially toxic are assembled for toxicity data collection. The data are first checked for correct chemical name and Chemical Abstracts Service (CAS) registry number, and the associated inventory disposition (e.g., release to water) is identified to help determine classification into different toxicity impact categories. Classification helps determine what toxicity data need to be collected. For example, if an inventory flow is released to water, it will require aquatic toxicity data.

For most of the chemicals identified in the inventory of the life-cycle of the solder alternatives being evaluated, toxicity data were collected for the CDP. For these chemicals, data from the CDP were used. For new chemicals identified in this LCA, chronic human toxicity endpoints and both acute and chronic aquatic toxicity endpoints were searched. The following specific endpoints are used for calculating human toxicity scores:

- inhalation or oral NOAEL (or inhalation or oral LOAEL),
- cancer slope factors, and
- cancer weight of evidence (WOE).

For ecological toxicity, the following endpoints are used for calculating aquatic toxicity:

- fish LC50, and
- fish NOEL.

In some cases, all endpoints needed to be searched, and in others, only aquatic toxicity endpoints need to be searched. This simply depended on what data were already available from the previous studies.

EPA's RAD provided guidance for collecting toxicity data for DfE Cleaner Technologies Substitutes Assessments. This served as the basis for data collection for this LCA; however, it was modified as applicable to an LCA. As stated in the RAD guidance, when searching for the toxicity endpoints, the first sources to be reviewed were to be:

- EPA’s Integrated Risk Information System (IRIS) (http://www.epa.gov/iris/),
- Agency for Toxic Substances and Disease Registry (ATSDR) toxicological profiles,
- EPA’s High Production Volume (HPV) Challenge robust summaries and supporting documents, and
- Organization for Economic Cooperation and Development’s (OECD’s) Screening Information Data Set (SIDS) robust summaries and supporting documents.

If endpoints from these sources were found, and did not conflict with other sources from this list, those data were chosen. Applicable data were included in a matrix of the chemicals and endpoints of interest and provided to UT by ORNL. If more than one value was found for an endpoint, decisions of what data to use were discussed between ORNL and UT and then UT and EPA.

If endpoints were not found from the above sources, the following databases were to be searched:

- Toxline,
- Medline (as appropriate, depending on the toxicity endpoint or endpoints for which data are being sought), and
- TSCATS (Toxic Substances Control Act Test Submissions)–the EPA database that holds data submitted to the Agency under TSCA sections 4 and 8). Although data in TSCATS may be unpublished and, therefore, not subjected to peer review by the editors of a journal, the data may provide useful information on particular chemicals and can be considered for preparation of robust summaries if the TSCATS data meet Agency standards for data quality/data adequacy.

For studies providing endpoint data found in these or other alternative sources, ORNL was instructed to prepare brief summaries of the studies (following the format of a robust summary to the extent possible, see www.epa.gov/chemrtk/robusumgd.htm). ORNL would then document which value was chosen and explain why. Consideration of EPA's criteria for data quality/data adequacy would also be incorporated into the explanation (www.epa.gov/opptintr/chemrtk/datadfin.htm).

Toxicity Data:

Table E-4 presents the final chosen toxicity data and, where necessary, provides comments on the selection process. Tables E-5, E-6, and E-7 provide the supporting toxicity data collected for the LFSP project by ORNL. The data in Tables E-5, E-6, and E-7 were reviewed by UT. The chosen data were then reviewed by EPA and the actual data points used in the LFSP life-cycle impact assessment (LCIA) are also provided in Table E-4.

The LCIA methodology is similar to that which was used for the CDP, and is described in Section 3.1 of this report. The toxicity data required for the LCIA, and what was requested from ORNL, are as follows:

- Cancer (mammalian toxicity)
    - oral SF
    - inhalation SF
    - WOE
- Non-cancer (mammalian toxicity)
    - oral NOAEL (or LOAEL)
    - inhalation NOAEL (or LOAEL)
- Aquatic ecotoxicity
    - LC50
    - NOEL

In the cases where chronic ecotoxicity (e.g., no observable effect level [NOEL]) data are not available, the log K_{ow} and the LC_{50} are used to predict the NOEL (described in Section 3.1.2.13). The log K_{ow} values were determined using the LOGKOW/KOWWIN Program found at the following address: http://esc.syrres.com/interkow/interkow.exe. Table E-5 provides the human health data and Table E-6 presents the aquatic toxicity data. When other data related to the toxicity of a chemical were readily available, such data were also reported as “other” toxicity values, which are provided in Table E-7.

For the LFSP, there were 11 chemicals for which both mammalian toxicity and aquatic ecotoxicity data were needed and seven chemicals for which only aquatic ecotoxicity data were needed (mammalian toxicity data were already available from previous projects for those seven chemicals). The remaining chemical inventory for the LFSP constitutes approximately 150 chemicals. Toxicity data from previous projects (e.g., the CDP) were used for those chemicals. The toxicity data used for all potentially toxic chemicals in the LFSP are presented in Table E-1.

Per guidance provided by RAD, ORNL was asked to first search the following sources for toxicity data: IRIS, ATSDR toxicological profiles, HPV challenge robust summaries and supporting documents, and SIDS robust summaries and supporting documents. If data were not found in these sources, Toxline, Medline and TSCATS were to be searched, also per RAD guidance. If data were used from these latter sources, ORNL was instructed to provide robust summaries for data. No data were used from these sources, thus no robust summaries were prepared by ORNL.

In cases where there was more than one data point, ORNL selected a data point based on the applicability of the study to the endpoint of interest and the robustness of the study (as best could be determined from the available data). In many cases, the original sources were not reviewed, but information from secondary sources (e.g., EPA’s ECOTOXicology Data Base System [U.S. EPA, 2002]) on the test type and duration were considered. The following hierarchy of fish studies, based on Swanson *et al.* 1997, was employed to choose LC_{50} ecotoxicity data in order of preference:

(1) fathead minnow 96-h flow-through test
(2) 96-h flow-through test for another freshwater fish, excluding trout
(3) fathead minnow 96-h static test
(4) 96-h static test for another freshwater fish, excluding trout

If the only adequate data were for trout, they would also be used. In cases where multiple data points (with equivalent quality, test type, and species type) were available, an average of those data was taken as the data point of interest. This was preferred over taking the most toxic response, as these data are used in relative ranking of chemicals and not to serve as protective exposure limits.

Other aquatic species (e.g., daphnia, algae) were not used in the original methodology used to develop the LCIA toxicity method used in this study (i.e., CHEMS-1, Swanson et al., 1997); however, this does not preclude future versions of this methodology from using other species besides fish, which would represent lower trophic levels (e.g., daphnia or algae).

E.2 GEOMETRIC MEAN DATA FOR CALCULATING TOXICITY HAZARD VALUES

Tables E-8 through E-12 provide the chemical-specific toxicity data used to calculate the geometric means for each toxicity endpoint. Table E-13 provides a summary of the geometric means of each endpoint. The data contributing to the geometric mean calculations were used for previous projects and this project did not attempt to verify each data point. The geometric means are used as the comparative basis for calculating the HVs as described in Sections 3.2.11 through 3.2.13.

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E.4 GLOSSARY OF TOXICITY COMPARISON TERMS

CC (Concentration of concern)
Calculated aquatic toxicity value derived by dividing the lowest chronic value in mg/L by ten.

EC50 (Effective Concentration 50)
A calculated dose of a substance which is expected to cause an effect on 50% of a defined animal population.

LDLo (Lethal Dose Low)
The lowest dose (other than LD50) of a substance introduced by any route, other than inhalation, over any given period of time in one or more divided portions and reported to have caused death in humans or animals.

LD50 (Lethal Dose 50)
A calculated dose of a substance which is expected to cause the death of 50% of a defined experimental animal population.

LC50 (Lethal Concentration 50)
A calculated concentration of a substance in air or water, which is expected to cause the death of 50% of a defined experimental animal population.

LOAEL (Lowest observable adverse effect level)

MCL (Maximum Contaminant Level)

The highest level of a contaminant that is allowed in drinking water. It is a national primary drinking water regulation established by EPA.

NOEL (No observable effect level)

NOAEL (No observable adverse effect level)

OEL (Occupational exposure limit)
The concentration of a substance in air, that a worker may safely be exposed to on a regular basis, usually for an 8 hour workday.

PEF (Potency equivalency factor)
A calculated carcinogenicity comparison of a substance, relative to (in this case benzo(a)pyrene) another substance.

PEL (Permissible exposure limit)
The 8-hour time weighted average for the concentration of a substance in air that must not be exceeded during any 8-hour workshift of a 40 hour work week.

TDLo (Toxic Dose Low)
The lowest dose of a substance reported to produce any toxic effect in humans or tumorigenic, reproductive, or multiple effects in animals.

TLm (Median tolerance limit)
A calculated dose which is expected to cause an effect (includes death) in 50% of a test population.

WOE (Weight of evidence)
Classification of relevance and quality of studies used to make a determination of carcinogenicity.

Table E-1. Toxicity data for potentially toxic LFSP chemicals

Cas #	Material (flow)	oral SF (mg/kg- day) ^{1}	inhal SF (mg/kg- day)$^{-1}$	WOE (EPA & IARC) (a)	oral NOAEL (b) (mg/kg-day)	inhal NOAEL (b) (mg/m^{3})	oral LOAEL (b,c) (mg/kg-day)	inhal LOAEL (b,c) (mg/m^{3})	fish LC$_{50}$ (mg/L)	fish NOEL (mg/L)
1746-01-6	2,3,7,8-TCDD (2,3,7,8-Tetrachlorodibenzo-p-Dioxin)	1.50E+05	1.50E+05	1	9.00E-08	X	X	X	XX	XX
51207-31-9	2,3,7,8-TCDF (2,3,7,8-Tetrachlorodibenzo Furan)	1.50E+04	1.50E+04	3	- -	- -	- -	- -	XX	XX
121-14-2	2,4-Dinitrotoluene	0.68	X	B2	0.2	X	X	X	24	6
91-57-6	2-Methylnaphthalene	- -	- -	- -	- -	- -	- -	- -	XX	XX
56-49-5	3-Methylcholanthrene	- -	- -	- -	X	X	2.86	X	XX	XX
3697-24-3	5-Methyl chrysene (category: PAH)	X	- -	2B	- -	- -	- -	- -	XX	XX
83-32-9	Acenaphthene (category: PAH)	- -	- -	- -	175	X	350	X	XX	XX
208-96-8	Acenaphthylene (category: PAH)	X	- -	D	- -	- -	- -	- -	XX	XX
75-07-0	Ethanal (Acetaldehyde)	X	7.70E-03	2B	125	300	X	X	34	9
64-19-7	Acetic acid	- -	- -	- -	195	X	X	X	XX	XX
67-64-1	Acetone	X	- -	D	100	X	X	X	720	180
98-86-2	Acetophenone	- -	- -	- -	423	X	X	X	XX	XX
107-02-8	Acrolein	X	- -	C,3	- -	- -	- -	- -	XX	XX
No CAS #	Aluminium (Al3+)	- -	- -	- -	- -	- -	- -	- -	3.6	0.36
7429-90-5	Aluminum (Al)	X	- -	SAR0	60	X	X	X	11	3.3
7664-41-7	Ammonia	- -	- -	- -	34	40	X	X	2	9.00E-02
6484-52-2	Ammonium nitrate									
120-12-7	Anthracene (category: PAH)	X	- -	SAR1	1000	X	X	X	0.01	- -
7440-36-0	Antimony (Sb)	- -	- -	- -	X	X	0.35	X	14.4	1.6
7440-38-2	Arsenic (As)	1.5	50	A	8.00E-04	X	X	X	14.4	2.1
7440-39-3	Barium (Ba)	- -	- -	- -	0.21	X	X	X	580	50
20-02-0	Barium compounds [Barium (Ba++)]	X	- -	D	0.21	X	X	X	200	10
71-43-2	Benzene	0.055	0.029	A,1	1	1.15	10	98	19	4
56-55-3	Benzo{a}anthracene (category: PAH)	0.73	0.31	B2	- -	- -	- -	- -	XX	XX
50-32-8	Benzo{a}pyrene	7.3	3.1	B2,2A	- -	- -	- -	- -	XX	XX
56832-73-6	Benzo{b,j,k}fluoranthene (category: PAH)	X	- -	B2	- -	- -	- -	- -	XX	XX
205-99-2	Benzo{b}fluoranthene	0.73	0.31	B2	- -	- -	- -	- -	XX	XX
191-24-2	Benzo{g,h,I}perylene (category: PAH)	X	- -	D	- -	- -	- -	- -	XX	XX
207-08-9	Benzo{k}fluoranthene	--	--	B2	--	--	--	--	1000	0.006
100-44-7	Benzyl chloride	0.17	X	B2,3	- -	- -	- -	- -	XX	XX
7440-41-7	Beryllium (Be)	4.3	8.4	X	X	X	X	5.50E-04	2	0.2
117-81-7	Bis(2-ethylhexyl)phthalate [Di(2-ethylhexyl)phthalate]	X	X	B2,2B	50	50	X	X	1	0.08
7440-69-9	Bismuth	--	--	--	3,243	--	--	--	5	0.5
1303-96-4	Borax	- -	- -	- -	- -	- -	- -	- -	XX	XX
No CAS #	Boron (B III)	- -	- -	- -	8.8	X	X	X	113	27
7440-42-8	Boron (B)	- -	- -	- -	8.8	X	X	X	113	27

Table E-1. Toxicity data for potentially toxic LFSP chemicals

Cas #	Material (flow)	oral SF (mg/kg- day)^{1}	inhal SF (mg/kg- day)$^{-1}$	WOE (EPA & IARC) (a)	oral NOAEL (b) (mg/kg-day)	inhal NOAEL (b) (mg/m^{3})	oral LOAEL (b,c) (mg/kg-day)	inhal LOAEL (b,c) (mg/m^{3})	fish LC_{50} (mg/L)	fish NOEL (mg/L)
7726-95-6	Bromine	- -	- -	- -	- -	- -	- -	- -	XX	XX
75-25-2	Bromoform	7.90E-03	3.90E-03	B2	17.9	X	X	X	XX	XX
7440-43-9	Cadmium (Cd)	X	6.1	B1,1	X	X	4.00E-02	2.20E-02	0.001	0.001
20-04-2	Cadmium cmpds (as CdCl2) [Cadmium (Cd++)]	X	- -	B1,2A	5.00E-03	X	X	X	0.1	- -
75-15-0	Carbon disulfide	- -	- -	- -	X	10	X	X	694	174
630-08-0	Carbon monoxide (CO)	- -	- -	- -	X	114.5	X	55	XX	XX
75-69-4	CFC 11 (Trichlorofluoromethane)	- -	- -	- -	X	X	349	X	XX	XX
76-14-2	CFC 114 (1,2-dichlorotetrafluoroethane)	- -	- -	- -	2.73E+02	X	X	X	XX	XX
75-71-8	CFC 12 (Dichlorodifluoromethane)	- -	- -	- -	15	X	X	X	XX	XX
75-72-9	CFC 13 (Dichlorotrifluoromethane)	- -	- -	- -	- -	- -	- -	- -	XX	XX
7782-50-5	Chlorine (Cl2)	- -	- -	- -	14	X	X	X	0.34	0.02
1341-24-8	Chloroacetophenone	- -	- -	- -	- -	- -	- -	- -	XX	XX
108-90-7	Chlorobenzene	X	- -	SAR0	12.5	377	X	X	17	2
16065-83-1	Chromium (Cr III)	X	- -	D	1468	X	X	X	3.3	0.33
7440-47-3	Chromium (Cr)	X	- -	1	- -	- -	- -	- -	52	5.2
18540-29-9	Chromium, hexavalent (Cr VI)	X	41	A,1	2.5	X	X	X	22.6	2.23
218-01-9	Chrysene (category: PAH)	7.30E-03	3.10E-03	X	- -	- -	- -	- -	XX	XX
7440-48-4	Cobalt (Co)	- -	- -	- -	- -	- -	- -	- -	XX	XX
7440-50-8	Copper (Cu)	X	- -	D	5.30E-01	X	X	X	1.40E-02	4.00E-03
No CAS #	Copper (Cu+, Cu++)	- -	- -	- -	5.30E-01	X	X	X	1.40E-02	4.00E-03
98-82-8	Cumene	X	- -	SAR0	154	537	X	X	6	0.49
57-12-5	Cyanide (CN)	X	- -	D	10.8	X	X	X	56	5.7
53-70-3	Dibenzo{a,h}anthracene	7.3	3.1	B2	- -	- -	- -	- -	XX	XX
25321-22-6	Dichlorobenzene (mixed isomers)	X	X	SAR0	X	610.4	X	X	1	0.05
107-06-2	Ethylene dichloride (Dichloroethane)	9.10E-02	9.10E-02	B2,2B	18	221	X	X	136	34
75-09-2	Dichloromethane (Methylene chloride)	7.50E-03	1.65E-03	B2,2B	155	796	X	X	330	83
77-78-1	Dimethyl sulfate	X	X	B1,2A	- -	- -	- -	- -	XX	XX
57-97-6	Dimethylbenzanthracene	- -	- -	- -	X	X	X	1.40E-02	XX	XX
74-84-0	Ethane	- -	- -	- -	- -	- -	- -	- -	XX	XX
75-00-3	Ethyl chloride	X	X	3	X	3600	X	X	16	4
100-41-4	Ethylbenzene	X	X	SAR0	136	2370	X	X	11	1
106-93-4	Ethylene dibromide	85	7.60E-01	B2	- -	- -	- -	- -	XX	XX
206-44-0	Fluoranthene (category: PAH)	X	X	D	125	X	X	X	XX	XX
86-73-7	Fluorene (category: PAH)	X	X	D	125	X	X	X	XX	XX
16984-48-8	Fluoride	- -	- -	- -	- -	- -	- -	- -	- -	- -
No CAS #	Fluorides (F-)	- -	- -	- -	6.00E-02	X	X	X	- -	- -

Table E-1. Toxicity data for potentially toxic LFSP chemicals

Cas #	Material (flow)	oral SF (mg/kg- day)^{1}	inhal SF (mg/kg- day)$^{-1}$	WOE (EPA & IARC) (a)	oral NOAEL (b) (mg/kg-day)	inhal NOAEL (b) (mg/m^3)	oral LOAEL (b,c) (mg/kg-day)	inhal LOAEL (b,c) (mg/m^3)	fish LC$_{50}$ (mg/L)	fish NOEL (mg/L)
7782-41-4	Fluorine (F2)	- -	- -	- -	6.00E-02	X	X	X	100	10
16872-11-0	Fluoroboric acid	--	--	--	--	--	0.77	--	1000	20
16961-83-4	Fluorosilicic acid	--	--	--	--	--	0.77	--	100	10
(d)	Flux A (d)	--	--	--	--	--	--	--	900	90
(d)	Flux B (d)	--	--	--	450	200	1000	810	930	100
(d)	Flux C (d)	- -	- -	- -	- -	- -	- -	- -	XX	XX
(d)	Flux D (d)	--	--	--	--	--	--	--	0.5	0.05
(d)	Flux E (d)	--	--	--	--	--	--	--	1000	100
(d)	Flux F (d)	--	--	--	--	--	--	--	1000	100
50-00-0	Formaldehyde (CH2O)	X	4.50E-02	B1,2A	15	0.6	X	X	24	6
No CAS #	Light Fuel Oil (#2, distillate and diesel)	- -	- -	- -	- -	- -	- -	- -	XX	XX
75-63-8	Halon 1301	- -	- -	- -	- -	- -	- -		XX	XX
75-45-6	HCFC 22 (Chlorodifluoromethane)	- -	- -	- -	X	5,260	X	X	XX	XX
110-54-3	Hexane	- -	- -	- -	X	X	X	73	2.5	0.25
7647-01-0	Hydrochloric acid	X	X	3	X	15	X	X	19	0.95
7664-39-3	Hydrofluoric acid (Hydrogen fluoride)	- -	- -	- -	- -	- -	- -	- -	265	13
74-90-8	Hydrogen Cyanide	X	X	SAR0	10.8	X	30	7.07	1,385	346
7783-06-4	Hydrogen Sulfide	- -	- -	- -	3.1	X	X	15	XX	XX
193-39-5	Indeno{1,2,3-cd}pyrene (category: PAH)	7.30E-01	3.10E-01	B2	- -	- -	- -	- -	XX	XX
1309-36-0	Iron pyrite	--	--	--	--	1	--	--	1000	--
78-59-1	Isophorone	9.50E-04	X	C	150	X	X	X	XX	XX
67-63-0	Isopropyl alcohol	X	X	1	230	268.3	X	X	8,623	2,156
7439-92-1	Lead (Pb)	X	X	B2,2B			0.014	0.011	31.5	0.004
20-11-1	Lead compounds (as PbCl2) [Lead (Pb++, Pb4+)]	X	X	B2,2B		- -	0.014	0.011	5	0.26
NA	Liquified petroleum gas (LPG)	- -	- -	- -	- -	- -	- -	- -	2600	260
7439-96-5	Manganese	X	X	D	0.14	X	X	0.15	- -	- -
	Mercaptan									
7439-97-6	Mercury (Hg)	X	X	D,3	X	6.00E-03	X	9.00E-03	0.155	0.005
no CAS#	Mercury cmpds (as HgCl2) [Mercury (Hg+, Hg++)]	X	X	C	X	X	0.226	X	0.155	0.005
	Metals, unspecified									
74-82-8	Methane (natural gas)	- -	- -	- -	- -	- -	- -	- -	XX	XX
67-56-1	Methanol	X	X	SAR0	500	130	X	X	29,400	7,350
74-83-9	Methyl bromide (bromomethane)	X	- -	C,3	0.4	4.3	X	X	11	3
74-87-3	Methyl chloride (Chloromethane)	1.30E-02	6.30E-03	C,3	X	1138.4	X	1550	550	138
78-93-3	Methyl ethyl ketone	X	X	D	125	8047	X	X	3,220	805
60-34-4	Methyl hydrazine	3	17.2	A3	- -	- -	- -	- -	XX	XX

Table E-1. Toxicity data for potentially toxic LFSP chemicals

Cas #	Material (flow)	oral SF (mg/kg- day)^{1}	inhal SF (mg/kg- day)$^{-1}$	WOE (EPA & IARC) (a)	oral NOAEL (b) (mg/kg-day)	inhal NOAEL (b) (mg/m^3)	oral LOAEL (b,c) (mg/kg-day)	inhal LOAEL (b,c) (mg/m^3)	fish LC$_{50}$ (mg/L)	fish NOEL (mg/L)
80-62-6	Methyl methacrylate	X	X	SAR0	7.5	111.7	X	X	259	65
1634-04-4	Methyl tert butyl ether (MTBE)	X	X	SAR0	100	2880	X	X	786	197
7439-98-7	Molybdenum (Mo)	- -	- -	- -	X	X	0.14	X	157	0.125
91-20-3	Naphthalene	X	X	C	71	X	X	9.3	6	0.59
7440-02-0	Nickel (Ni)	X	X	A	5	X	X	X	2.48	0.09
20-14-4	Nickel cmpds (as NiCl2) [Nickel (Ni++, Ni3+)]	X	X	A,1	- -	- -	- -	- -	27	1
14797-55-8	Nitrates	- -	- -	- -	1.6	X	X	X	2,213	213
no CAS#	Nitrogen Oxides (NOx)	- -	- -	- -	- -	- -	- -	- -	XX	XX
10024-97-2	Nitrous oxide	- -	- -	- -	- -	- -	- -	- -	XX	XX
NA	Particulate matter (PM-10) [Particulates < 10 microns]	- -	- -	- -	- -	- -	- -	- -	XX	XX
NA	Particulate matter, total (PM)	- -	- -	- -	- -	- -	- -	- -	XX	XX
109-66-0	Pentane	X	X	D	- -	- -	- -	- -	XX	XX
85-01-8	Phenanthrene (category: PAH)	X	X	D	- -	- -	- -	- -	XX	XX
108-95-2	Phenol	X	X	D,3	60	X	X	X	34	8
7723-14-0	Phosphorus	X	X	D	1.50E-02	X	X	X	0.02	- -
123-38-6	Propionaldehyde	X	X	SAR3	X	200	X	X	44	11
115-07-1	Propylene (Propene)	X	X	SAR0	X	9375	X	X	5	1
129-00-0	Pyrene (category: PAH)	X	X	D	75	X	X	X	XX	XX
7440-20-2	Scandium (Sc)	- -	- -	- -	- -	- -	- -	- -	XX	XX
7782-49-2	Selenium (Se)	X	X	D	1.50E-02	X	X	X	4.9	0.1
7440-21-3	Silicon (Si)	- -	- -	- -	- -	- -	- -	- -	XX	XX
7440-22-4	Silver	X	X	D	X	X	1.40E-02	X	4.00E-03	0.001
7681-52-9	Sodium Hypochlorite	X	X	3	2.1	X	X	X	0.53	0.05
7440-24-6	Strontium (Sr)	- -	- -	- -	190	X	X	X	210	20
100-42-5	Styrene	X	X	C,2B	100	565	X	X	4	0.44
7446-09-5	Sulfur dioxide	X	X	3	X	0.104	X	X	XX	XX
no CAS#	Sulfur oxides (SOx)	- -	- -	- -	- -	- -	- -	- -	XX	XX
7664-93-9	Sulfuric acid	X	X	1	X	0.1	X	X	31	2
127-18-4	Tetrachloroethylene (Perchloroethylene)	5.20E-02	2.00E-03	B2,2B	14	740.2	X	X	17	2
7440-28-0	Thallium (TI)	- -	- -	- -	- -	- -	- -	- -	XX	XX
7440-31-5	Tin (Sn)	- -	- -	- -	- -	- -	- -	- -	626	62.6
7440-32-6	Titanium	X	X	C	X	0.8	1146	X	- -	- -
108-88-3	Toluene	X	X	D,3	100	411.1	X	X	34	4
71-55-6	Trichloroethane (1,1,1-trichloroethane)	- -	- -	- -	2.50E+02	1.21E+03	X	X	48	7
67-66-3	Trichloromethane (Chloroform)	6.10E-03	8.10E-02	B2,2B	X	X	12.9	X	71	18
7440-62-2	Vanadium (V)	- -	- -	- -	3.00E-03	X	X	X	4	0.67

Table E-1. Toxicity data for potentially toxic LFSP chemicals

Cas #	Material (flow)	oral SF (mg/kg- day)^{1}	inhal SF (mg/kg- day)$^{-1}$	WOE (EPA & IARC) (a)	oral NOAEL (b) (mg/kg-day)	inhal NOAEL (b) (mg/m^{3})	oral LOAEL (b,c) (mg/kg-day)	inhal LOAEL (b,c) (mg/m^{3})	fish LC$_{50}$ (mg/L)	fish NOEL (mg/L)
108-05-4	Vinyl acetate	X	X	SAR0	100	176	X	X	100	25
1330-20-7	Xylene (C24H30) [mixed isomers]	X	X	D	179	X	X	X	13	1
7440-66-6	Zinc (Zn)	X	X	D	0.9	X	1	X	9.00E-02	0.036
No CAS #	Zinc (Zn++)	- -	- -	- -	- -	- -	- -	- -	14	0.8
7733-02-0	Zinc sulfate	--	--	D	--	--	1	--	1.27	--

Key:

(a)=See Table 3-72 in Section 3.2.11.1 for a description of WOE classifications.

(b)=Only lowest value of the NOAEL (or LOAEL/10) is used to calculate chronic, non-cancer effects.

(c)=LOAEL only needed if no NOAEL found.

(d)=Flux material names and CAS#s have been withheld to protect confidentiality.

XX=Aquatic toxicity data not needed because there are no waterborne releases of this chemical in the LFSP inventories.

X=Data not needed because other data are provided to calculate impact score (e.g., LOAEL not needed if NOAEL provided, and WOE used if SF not available).

SAR0=Not a probable carcinogen based on structure-activity relationship (SAR) evaluation.

SAR1=Possible carcinogen based on SAR evaluation.

- - =No data available, defaulted to mean hazard value (see Section 3.1.2.12 for an explanation of hazard values).

Sources:

Oral and inhalation slope factors (SF): Integrated Risk Information System (IRIS) or Health Effects Assessment Summary Tables (HEAST) (EPA, 1994) as cited in Risk Assessment Information System (RAIS): http://risk.lsd.ornl.gov/rap_hp.shtml.

Weight of Evidence (WOE): IRIS Web site (http://www.epa.gov/IRIS).

Oral no observable adverse effect level (NOAEL), inhalation NOAEL, oral lowest obserable adverse effect level (LOAEL) and inhalation LOAEL: IUCLID, 1996; HEAST, 1994; Kincaid and Geibig, 1998; EPA, 2000a; SRC, 2000; EPA, 2000b; Geibig and Swanson, 2000; Sax and Lewis, 1987; NIOSH, 1978; EPA, 1984; and EPA, 1987.

Fish LC50 and fish NOAEL: EPA, 2001; HSDB; Davis et al. 1994, Appendix E; and Geiger et al., 1984, 1985, 1986, 1988, 1990.

Sources associated with data collected from ORNL (May, 2003) are listed in this Appendix under the References Section E.3.

Table E-2. Toxicity hazard values (HV) for potentially toxic chemicals in the LFSP

CAS#	Material (flow)	Cancer HV	Non-cancer HV	Aquatic ecotoxicity HV
1746-01-6	2,3,7,8-TCDD (2,3,7,8-Tetrachlorodibenzo-p-Dioxin)	2.11E+05	1.56E+08	not searched
51207-31-9	2,3,7,8-TCDF (2,3,7,8-Tetrachlorodibenzo Furan)	2.11E+04	1.00E+00	not searched
121-14-2	2,4-Dinitrotoluene	9.58E-01	7.00E+01	1.68E+00
91-57-6	2-Methylnaphthalene	1.00E+00	1.00E+00	not searched
56-49-5	3-Methylcholanthrene	1.00E+00	4.90E+01	not searched
3697-24-3	5-Methyl chrysene (category: PAH)	1.00E+00	1.00E+00	not searched
83-32-9	Acenaphthene (category: PAH)	1.00E+00	8.00E-02	not searched
208-96-8	Acenaphthylene (category: PAH)	0.00E+00	1.00E+00	not searched
75-07-0	Ethanal (Acetaldehyde)	4.53E-03	2.29E-01	1.16E+00
64-19-7	Acetic acid	1.00E+00	7.18E-02	not searched
67-64-1	Acetone	0.00E+00	1.40E-01	5.58E-02
98-86-2	Acetophenone	1.00E+00	3.31E-02	not searched
107-02-8	Acrolein	1.00E+00	1.00E+00	not searched
No CAS #	Aluminium (Al3+)	1.00E+00	1.00E+00	1.77E+01
7429-90-5	Aluminum (Al)	0.00E+00	2.33E-01	3.42E+00
7664-41-7	Ammonia	1.00E+00	1.72E+00	5.56E+01
120-12-7	Anthracene (category: PAH)	1.00E+00	1.40E-02	8.88E+03
7440-36-0	Antimony (Sb)	1.00E+00	4.00E+02	4.15E+00
7440-38-2	Arsenic (As)	2.94E+01	1.75E+04	3.57E+00
7440-39-3	Barium (Ba)	1.00E+00	6.67E+01	1.20E-01
20-02-0	Barium compounds [Barium (Ba++)]	0.00E+00	6.67E+01	5.13E-01
71-43-2	Benzene	7.75E-02	5.97E+01	2.27E+00
56-55-3	Benzo{a}anthracene (category: PAH)	1.03E+00	1.00E+00	not searched
50-32-8	Benzo{a}pyrene	1.03E+01	1.00E+00	not searched
56832-73-6	Benzo{b,j,k}fluoranthene (category: PAH)	1.00E+00	1.00E+00	not searched
205-99-2	Benzo{b}fluoranthene	1.03E+00	1.00E+00	not searched
191-24-2	Benzo{g,h,I}perylene (category: PAH)	0.00E+00	1.00E+00	not searched
207-08-9	benzo{k}fluoranthene	1.00E+00	1.00E+00	6.50E+02
100-44-7	Benzyl chloride	2.39E-01	1.00E+00	not searched
7440-41-7	Beryllium (Be)	6.06E+00	1.25E+06	3.18E+01
117-81-7	Bis(2-ethylhexyl)phthalate [Di(2-ethylhexyl)phthalate]	1.00E+00	1.37E+00	7.34E+01
7440-69-9	Bismuth	1.00E+00	4.32E-03	1.27E+01
1303-96-4	Borax	1.00E+00	1.00E+00	not searched
No CAS #	Boron (B III)	1.00E+00	1.59E+00	3.62E-01
7440-42-8	Boron (B)	1.00E+00	1.59E+00	3.62E-01
7726-95-6	Bromine	1.00E+00	1.00E+00	not searched
75-25-2	Bromoform	1.11E-02	7.82E-01	not searched
No CAS #	BSA (bismuth-tin-silver) alloy*	9.90E-01	1.00E+02	not searched
7440-43-9	Cadmium (Cd)	3.59E+00	3.12E+04	2.85E+04
20-04-2	Cadmium cmpds (as CdCl2) [Cadmium (Cd++)]	1.00E+00	2.80E+03	2.47E+02
75-15-0	Carbon disulfide	1.00E+00	6.87E+00	5.79E-02
630-08-0	Carbon monoxide (CO)	1.00E+00	6.00E-01	not searched
75-69-4	CFC 11 (Trichlorofluoromethane)	1.00E+00	4.01E-01	not searched
76-14-2	CFC 114 (1,2-dichlorotetrafluoroethane)	1.00E+00	5.13E-02	not searched
75-71-8	CFC 12 (Dichlorodifluoromethane)	1.00E+00	9.33E-01	not searched
75-72-9	CFC 13 (Dichlorotrifluoromethane)	1.00E+00	1.00E+00	not searched

Table E-2. Toxicity hazard values (HV) for potentially toxic chemicals in the LFSP

CAS#	Material (flow)	Cancer HV	Non-cancer HV	Aquatic ecotoxicity HV
7782-50-5	Chlorine (Cl2)	1.00E+00	1.00E+00	2.67E+02
1341-24-8	Chloroacetophenone	1.00E+00	1.00E+00	not searched
108-90-7	Chlorobenzene	0.00E+00	1.12E+00	3.40E+00
16065-83-1	Chromium (Cr III)	0.00E+00	9.54E-03	1.93E+01
7440-47-3	Chromium (Cr)	1.00E+00	1.00E+00	1.22E+00
18540-29-9	Chromium, hexavalent (Cr VI)	2.41E+01	5.60E+00	2.84E+00
218-01-9	Chrysene (category: PAH)	1.03E-02	1.00E+00	not searched
7440-48-4	Cobalt (Co)	1.00E+00	1.00E+00	not searched
7440-50-8	Copper (Cu)	0.00E+00	2.64E+01	2.73E+03
No CAS #	Copper (Cu+, Cu++)	1.00E+00	2.64E+01	2.73E+03
98-82-8	Cumene	0.00E+00	1.28E-01	1.21E+01
57-12-5	Cyanide (CN)	0.00E+00	1.30E+00	1.12E+00
53-70-3	Dibenzo{a,h}anthracene	1.03E+01	1.00E+00	not searched
25321-22-6	Dichlorobenzene (mixed isomers)	0.00E+00	1.13E-01	1.03E+02
107-06-2	Ethylene dichloride (Dichloroethane)	1.28E-01	7.78E-01	2.96E-01
75-09-2	Dichloromethane (Methylene chloride)	1.06E-02	9.03E-02	1.22E-01
77-78-1	Dimethyl sulfate	1.00E+00	1.00E+00	not searched
57-97-6	Dimethylbenzanthracene	1.00E+00	4.91E+04	not searched
74-84-0	Ethane	1.00E+00	1.00E+00	not searched
75-00-3	Ethyl chloride	0.00E+00	1.91E-02	2.51E+00
100-41-4	Ethylbenzene	0.00E+00	1.03E-01	6.14E+00
106-93-4	Ethylene dibromide	1.20E+02	1.00E+00	not searched
206-44-0	Fluoranthene (category: PAH)	0.00E+00	1.12E-01	not searched
86-73-7	Fluorene (category: PAH)	0.00E+00	1.12E-01	not searched
16984-48-8	Fluoride	1.00E+00	1.00E+00	2.00E+00
No CAS #	Fluorides (F-)	1.00E+00	2.33E+02	2.00E+00
7782-41-4	Fluorine (F2)	1.00E+00	2.33E+02	6.36E-01
16872-11-0	Fluoroboric acid	1.00E+00	1.82E+02	2.20E-01
16961-83-4	Fluorosilicic acid	1.00E+00	1.82E+02	6.36E-01
(d)	Flux A (d)	1.00E+00	1.00E+00	7.07E-02
(d)	Flux B (d)	1.00E+00	3.43E-01	6.55E-02
(d)	Flux C (d)	1.00E+00	1.00E+00	1.00E+00
(d)	Flux D (d)	1.00E+00	1.00E+00	1.27E+02
(d)	Flux E (d)	1.00E+00	1.00E+00	6.36E-02
(d)	Flux F (d)	1.00E+00	1.00E+00	6.36E-02
50-00-0	Formaldehyde (CH2O)	2.65E-02	1.14E+02	1.68E+00
No CAS #	Fuel Oil, light (#2, distillate and diesel)	1.00E+00	1.00E+00	not searched
75-63-8	Halon 1301	1.00E+00	1.00E+00	not searched
75-45-6	HCFC 22 (Chlorodifluoromethane)	1.00E+00	1.31E-02	not searched
110-54-3	Hexane	1.00E+00	9.41E+00	2.54E+01
7647-01-0	Hydrochloric acid	0.00E+00	4.58E+00	5.40E+00
7664-39-3	Hydrofluoric acid (Hydrogen fluoride)	1.00E+00	1.00E+00	3.93E-01
74-90-8	Hydrogen Cyanide	0.00E+00	1.30E+00	2.90E-02
7783-06-4	Hydrogen Sulfide	1.00E+00	4.52E+00	not searched
193-39-5	Indeno{1,2,3-cd}pyrene (category: PAH)	1.03E+00	1.00E+00	not searched
1309-36-0	Iron pyrite	1.00E+00	6.87E+01	1.03E-01

Table E-2. Toxicity hazard values (HV) for potentially toxic chemicals in the LFSP

CAS#	Material (flow)	Cancer HV	Non-cancer HV	Aquatic ecotoxicity HV
78-59-1	Isophorone	1.34E-03	9.33E-02	not searched
67-63-0	Isopropyl alcohol	1.00E+00	2.56E-01	4.66E-03
7439-92-1	Lead (Pb)	1.00E+00	6.24E+04	9.76E+02
20-11-1	Lead compounds (as PbCl2) [Lead (Pb++, Pb4+)]	1.00E+00	6.24E+04	1.99E+01
No CAS #	Liquified petroleum gas (LPG)	1.00E+00	1.00E+00	2.45E-02
7439-96-5	Manganese	0.00E+00	1.00E+02	2.00E+00
7439-97-6	Mercury (Hg)	0.00E+00	1.14E+04	9.39E+02
no CAS#	Mercury cmpds (as HgCl2) [Mercury (Hg+, Hg++)]	1.00E+00	6.19E+02	9.39E+02
74-82-8	Methane (natural gas)	1.00E+00	1.00E+00	not searched
67-56-1	Methanol	0.00E+00	5.28E-01	1.37E-03
74-83-9	Methyl bromide (bromomethane)	1.00E+00	3.50E+01	3.54E+00
74-87-3	Methyl chloride (Chloromethane)	1.83E-02	6.03E-02	7.30E-02
78-93-3	Methyl ethyl ketone	0.00E+00	1.12E-01	1.25E-02
60-34-4	Methyl hydrazine	1.01E+01	1.00E+00	not searched
80-62-6	Methyl methacrylate	0.00E+00	1.87E+00	1.55E-01
1634-04-4	Methyl tert butyl ether (MTBE)	0.00E+00	1.40E-01	5.11E-02
7439-98-7	Molybdenum (Mo)	1.00E+00	1.00E+03	3.14E+01
91-20-3	Naphthalene	1.00E+00	1.97E-01	1.07E+01
7440-02-0	Nickel (Ni)	1.00E+00	2.80E+00	5.33E+01
20-14-4	Nickel cmpds (as NiCl2) [Nickel (Ni++, Ni3+)]	1.00E+00	1.00E+00	4.81E+00
14797-55-8	Nitrates	1.00E+00	8.75E+00	2.94E-02
no CAS#	Nitrogen Oxides (NOx)	1.00E+00	1.00E+00	not searched
10024-97-2	Nitrous oxide	1.00E+00	1.00E+00	not searched
NA	Particulate matter (PM-10) [Particulates < 10 microns]	1.00E+00	1.00E+00	not searched
NA	Particulate matter, total (PM)	1.00E+00	1.00E+00	not searched
109-66-0	Pentane	0.00E+00	1.00E+00	not searched
85-01-8	Phenanthrene (category: PAH)	0.00E+00	1.00E+00	not searched
108-95-2	Phenol	0.00E+00	2.33E-01	1.21E+00
7723-14-0	Phosphorus	0.00E+00	9.33E+02	5.13E+03
123-38-6	Propionaldehyde	1.00E+00	3.43E-01	9.14E-01
115-07-1	Propylene (Propene)	0.00E+00	7.32E-03	8.82E+00
129-00-0	Pyrene (category: PAH)	0.00E+00	1.87E-01	not searched
7440-20-2	Scandium (Sc)	1.00E+00	1.00E+00	not searched
7782-49-2	Selenium (Se)	0.00E+00	9.33E+02	4.40E+01
7440-21-3	Silicon (Si)	1.00E+00	1.00E+00	not searched
7440-22-4	Silver	0.00E+00	1.00E+04	1.01E+04
no CAS #	SAC (tin-silver-copper) alloy*	9.55E-01	3.91E+02	not searched
no CAS #	SABC (tin-silver-bismuth-copper) alloy*	9.70E-01	2.51E+02	not searched
no CAS #	SnCu (in-copper) alloy*	9.92E-01	1.20E+00	not searched
no CAS #	SnPb (tin-lead) alloy*	1.00E+00	2.31E+04	not searched
7681-52-9	Sodium Hypochlorite	0.00E+00	6.67E+00	1.24E+02
7440-24-6	Strontium (Sr)	1.00E+00	7.37E-02	3.12E-01
100-42-5	Styrene	1.00E+00	1.40E-01	1.50E+01
7446-09-5	Sulfur dioxide	0.00E+00	6.60E+02	not searched
no CAS#	Sulfur oxides (SOx)	1.00E+00	1.00E+00	not searched
7664-93-9	Sulfuric acid	1.00E+00	6.87E+02	2.74E+00

Table E-2. Toxicity hazard values (HV) for potentially toxic chemicals in the LFSP

CAS#	Material (flow)	Cancer HV	Non-cancer HV	Aquatic ecotoxicity HV
127-18-4	Tetrachloroethylene (Tetrachloroethene, Perchloroethyl	7.32E-02	1.00E+00	3.40E+00
7440-28-0	Thallium (TI)	1.00E+00	1.00E+00	not searched
7440-31-5	Tin (Sn)	1.00E+00	1.00E+00	1.02E-01
7440-32-6	Titanium	1.00E+00	8.58E+01	2.00E+00
108-88-3	Toluene	0.00E+00	1.67E-01	1.70E+00
71-55-6	Trichloroethane (1,1,1-trichloroethane)	1.00E+00	5.68E-02	1.07E+00
67-66-3	Trichloromethane (Chloroform)	4.76E-02	1.09E+01	5.63E-01
7440-62-2	Vanadium (V)	1.00E+00	4.67E+03	1.20E+01
108-05-4	Vinyl acetate	0.00E+00	3.90E-01	4.02E-01
1330-20-7	Xylene (C24H30) [mixed isomers]	0.00E+00	7.82E-02	5.79E+00
7440-66-6	Zinc (Zn)	0.00E+00	1.56E+01	3.82E+02
No CAS #	Zinc (Zn++)	1.00E+00	1.00E+00	6.63E+00
7733-02-0	Zinc sulfate	0.00E+00	1.40E+02	8.08E+01

Key:

CAS=Chemical Abstracts Service.

HV=Hazard value. The methodologies for calculating the HVs are in Sections 3.2.11 through 3.2.13.

not searched=aquatic ecotoxicity HV was not needed for the LFSP and thus toxicity data were not collected.

*HVs for each solder alloy were calculated as a weighted average of the HV for each comoponent metal in the alloy.

Table E-3. Materials excluded from toxic classification

CAS#	Material (flow)	Reason for exclusion
NA	BOD (Biological Oxygen Demand)	judgement
106-97-8	Butane (n-C4H10)	GRAS
7440-70-2	Calcium (Ca)	judgement
124-38-9	Carbon Dioxide (CO2)	judgement
NA	Carbonate ion [Carbonates (CO3--, HCO3-, CO2]	judgement
NA	Charcoal	judgement
NA	COD (Chemical Oxygen Demand)	judgement
16887-00-6	Chloride (Cl-)	judgement
NA	Dissolved solids	judgement
64-17-5	Ethanol (Ethyl Alcohol)	GRAS
7440-59-7	Helium (He)	GRAS
7439-89-6	Iron (Fe)	judgement
NA	Iron (Fe++, Fe3+)	judgement
8008-20-6	Kerosene	judgement
7727-37-9	Nitrogen	GRAS
74-98-6	n-Propane [Propane (C3H8)]	GRAS
NA	Phosphates (PO4-3)	judgement
79-09-4	Propionic Acid	GRAS
NA	Salts (unspecified)	judgement
NA	Sawdust	judgement
7440-23-5	Sodium (Na)	judgement
NA	Sodium (Na+)	judgement
497-19-8	Sodium carbonate (Na2CO3, soda ash)	judgement
1310-73-2	Sodium hydroxide (NaOH)	judgement
14808-79-8	Sulfates (SO4--)	judgement
18496-25-8	Sulfides (S--)	judgement
14265-45-3	Sulfites (SO3--)	judgement
7704-34-9	Sulfur	judgement
NA	Suspended Solids	judgement
NA	TOCs (Total organic compounds)	judgement

CAS#=Chemical Abstracts Service Registry Number

NA=not applicable

GRAS="Generally Regarded as Safe" according to the U.S. Food and Drug Admimistration

Table E-4. FINAL TOXICITY DATA SELECTIONS FOR USE IN THE LCIA

Cas #	Material	Selection comments by UT	oral or inhal SF	WOE (EPA & IARC)	oral NOAEL (mg/kg-day)	inhal NOAEL (mg/m3)	oral LOAEL (a) (mg/kg-day)	inhal LOAEL (a) (mg/m3)	fish LC50 (mg/L)	fish NOEL (mg/L)
For human and ecological endpoints:										
207-08-9	Benzo(k)fluoranthene	inhalation NOAEL not used as it is an occupational limit, presumably including safety and/or uncertainty factors, thus not consistent with a NOAEL; no supporting NOAEL or LOAEL found; therefore, assume "no data"	--	B2	--	--	--	--	**	0.006
16872-11-0	Fluoroboric acid	inhalation NOAEL not used as it is an occupational limit, presumably including safety and/or uncertainty factors; therefore, not consistent with a NOAEL; no supporting NOAEL or LOAEL found; therefore, assume "no data." The NOAEL is actually a dermal "NOAEL/LOAEL" as reported in the PWB CTSA (USEPA 1998a)	--	--	--	--	0.77	--	>1000	>=20
16961-83-4	Fluorosilicic acid	inhalation NOAEL not used as it is an occupational limit, presumably including safety and/or uncertainty factors; therefore, not consistent with a NOAEL; no supporting NOAEL or LOAEL found; therefore, assume "no data." The NOAEL is actually a dermal "NOAEL/LOAEL" as reported in the PWB CTSA (USEPA 1998a)	--	--	--	--	0.77	--	>100	>10
(b)	Flux A		--	--	--	--	--	--	900	90
(b)	Flux B		--	--	450	200	1000	810	930	100
(b)	Flux D	the fish LC50 is based on same chemical name, but with a different CAS# than we were provided	--	--	--	--	--	--	<=0.5	<=0.05
(b)	Flux E		--	--	--	--	--	--	>1000	>100
(b)	Flux F	since the source of the LC50 data does not supply the original data source of the toxicity value, we chose to use the ECOSAR estimate	--	--	500	--	--	--	5.4	0.87
1309-36-0	Iron pyrite	inhalation NOAEL not used as it is an occupational limit, presumably including safety and/or uncertainty factors, thus not consistent with a NOAEL; no supporting NOAEL or LOAEL found; therefore, assume "no data"	--	--	--	--	--	--	**	**
7733-02-0	Zinc sulfate	chose fathead minnow data (1.27 mg/L) instead of rainbow trout data; based on our methodology (i.e., exclude trout data due to species sensitivity) (Swanson et al. 1997)	--	D	--	--	1	--	14	0.8
7440-69-9	Bismuth	for oral NOAEL, converted 227 g/d using 70 kg body weight; didn't use inhalation NOAEL as it is a PEL (occupational limit) which incorporates time-weighted exposure and possibly safety and/or uncertainty factors and thus not consistent with a NOAEL	--	3243	--	--	--	--	5	0.5
For fish LC50 and fish NOEL endpoints only:										

Table E-4. FINAL TOXICITY DATA SELECTIONS FOR USE IN THE LCIA

Cas #	Material	Selection comments by UT	oral or inhal SF	WOE (EPA & IARC)	oral NOAEL (mg/kg-day)	inhal NOAEL (mg/m3)	oral LOAEL (a) (mg/kg-day)	inhal LOAEL (a) (mg/m3)	fish LC50 (mg/L)	fish NOEL (mg/L)
7429-90-5	Aluminum	took average of LC50s							11	3.3
7440-41-7	Beryllium								2	0.2
7782-41-4	Fluorine	took average of LC50s							>100	>10
7782-49-2	Selenium	took average of LC50s							4.9	0.1
7681-52-9	Sodium Hypochlorite	took average of LC50s							0.530 (measured)	<=0.05
7440-24-6	Strontium	took average of LC50s							210	20
7440-62-2	Vanadium	used rainbow trout listed in fish LC50 column, as fathead minnow data source had no date and did not provide time period of the test							4	0.67

Notes:
Dark shading indicates data are not needed
(a) LOAEL only needed if no NOAEL found (LOAEL/10 will be used to represent NOAEL)
(b) Flux material names and CAS#s have been withheld to protect confidentiality
-- = no data
** = low toxicity

Table E-5. HUMAN HEALTH TOXICITY DATA COLLECTION

Cas #	Material	oral SF (mg/kg-day)-1	inhal SF (mg/kg-day)-1	WOE (EPA & IARC)	Source*	oral NOAEL (mg/kg-day)	Source*	inhal NOAEL (mg/m3)	Source*	oral LOAEL (a) (mg/kg-day)	Source*	inhal LOAEL (a) (mg/m3)	Source*
Searched for human and ecological toxicity endpoints:													
207-08-9	Benzo(k)fluoranthene	N/A	N/A	**B2**	U.S. EPA, 1997	N/A		0.04 (Norway OEL, human)	RTECS, 2003b	N/A		N/A	
16872-11-0	Fluoroboric acid	N/A	N/A	N/A		N/A		2.5 as F (human, 8-10 hr/day, 5 d/wk)	U.S. CFR, 1994, NIOSH, 1997	**0.77** (for fluorides; human; 2 yr; bone, joint and G.I. effects)	U.S. EPA, 1998a	N/A	
16961-83-4	Fluorosilicic acid	N/A	N/A	N/A		N/A		2.5 as F (human, 8-10 hr/day, 5 d/wk)	U.S. CFR, 1994, NIOSH, 1997	**0.77** (for fluorides; human; 2 yr; bone, joint and G.I. effects)	U.S. EPA, 1998a	N/A	
(b)	Flux A	data withheld for confidentiality											
(b)	Flux B	data withheld for confidentiality											
(b)	Flux D	data withheld for confidentiality											
(b)	Flux E	data withheld for confidentiality											
(b)	Flux F	data withheld for confidentiality											
1309-36-0	Iron pyrite	N/A	N/A	N/A		N/A		1.0 (for iron salts, soluble as iron, human, 8 hr/day, 5 d/wk	ACGIH, 2002	N/A		N/A	
7733-02-0	Zinc sulfate	N/A	N/A	**D**	U.S. EPA 1998b	N/A		N/A		**1.0** (human; zinc cmpds. as zinc)	U.S. EPA 1998b	N/A	
7440-69-9	Bismuth	N/A	N/A	N/A		**227**g/d (human, 3 wk)	HSDB, 2003	2.5 (PEL for 8 hr day, 5 d/wk, for bismuth fluoride)	U.S. CFR, 1994	221 mg/kg (LDLo, human)	Arena, 1970	N/A	

Notes:
(a) LOAEL only needed if no NOAEL found (LOAEL/10 will be used to represent NOAEL)
Cancer WOE B2 = Probable human carcinogen
Cancer WOE D = Not classifiable as to human carcinogenicity
* Full citations of sources are provided in the References section of this Appendix (E.3)
(b) Flux material names and CAS#s have been withheld to protect confidentiality
BOLD indicates values used for LFSP

Table E-6. AQUATIC TOXICITY DATA COLLECTION

Cas #	Material	fish LC50 (mg/L)	Source*	fish NOEL (mg/L)	Source*	ECOSAR LC50 mg/L (predicted 96-hr)	ECOSAR Chronic mg/L (predicted)	Source*
207-08-9	Benzo(k)fluoranthene	**0.026** (96 hr predicted value for fish exceeds water solubility)	U.S.EPA, 2003a	NA		**	**0.006**	U.S.EPA, 2003b
16872-11-0	Fluoroboric acid	NA		N/A		**>1000**	**>=20**	U.S.EPA, 2003b
16961-83-4	Fluorosilicic acid	49 (as sodium fluorosilicate, bluegill, 96 hr)	Dawson et al., 1977	N/A		**>100**	**>10**	U.S.EPA, 2003b
(a)	Flux A	data withheld for confidentiality						
(a)	Flux B	data withheld for confidentiality						
(a)	Flux D	data withheld for confidentiality						
(a)	Flux E	data withheld for confidentiality						
(a)	Flux F	data withheld for confidentiality						
1309-36-0	Iron pyrite	6746.128 (96 hr predicted LC50); report as **>1000**	U.S. EPA, 2002	N/A		**	**	U.S.EPA, 2003b
7733-02-0	Zinc sulfate	1.27 (fathead minnow, 96 hr LC50)	Erten-Unal, et al., 1998	N/A		**14.0**	**0.800**	U.S.EPA, 2003b
7440-69-9	Bismuth	N/A		N/A		**5.0**	**0.500**	U.S.EPA, 2003b
7429-90-5	Aluminum	0.12,0.16,0.31 (rainbow trout; static, 96 hr)	Holtze, 1983	N/A		**11.0**	**3.3**	U.S.EPA, 2003b
7440-41-7	Beryllium	37.9 (fathead minnow; time not given)	Cardwell et al., 1976	N/A		**2.0**	**0.200**	U.S.EPA, 2003b
7782-41-4	Fluorine	51, 128, 140, 193, 107.5, 200 (as sodium fluoride, rainbow trout, 96 hr static)	Pimentel & Bulkley, 1983; Smith et al., 1985, Camargo and Tarazona, 1991	N/A		**>100**	**>10**	U.S.EPA, 2003b
7782-49-2	Selenium	11.5, 12.5, 45, 48 (rainbow trout, 96 hr)	Goettl et al., 1976; Spehar 1986	N/A		**4.9**	**0.100**	U.S.EPA, 2003b
7681-52-9	Sodium Hypochlorite	0.08,5.9,1.56,0.44,1.37,0.39,0.58,0.18,0.17,0.79,0.14,0.72,0.35,10(fathead minnow, 96 hr)	Ewell, et al., 1986; Wilde, et al., 1983a, Wilde, et al., 1983b, Curtis et al., 1979	N/A		**0.530 (measured)**	**<=0.05**	U.S.EPA, 2003b
7440-24-6	Strontium	>0.17-<15.61(rainbow trout, 28 day)	Birge et al., 1979	N/A		**210**	**20.0**	U.S.EPA, 2003b
7440-62-2	Vanadium	0.16 (rainbow trout, 28 day)	Birge et al., 1979	N/A		**4.0**	**0.670**	U.S.EPA, 2003b

Notes:
(a) Flux material names and CAS#s have been withheld to protect confidentiality
* Full citations of sources are provided in the References section of this Appendix (E.3)
ECOSAR data in last columns were done by EPA after ORNL's search
where >/<, used absolute values
** = low toxicity
BOLD indicates values used for LFSP

Table E-7. OTHER TOXICITY-RELATED DATA

Cas #	Material	Other Mammalian Toxicity value	Source*	Other Aquatic Toxicity Value (mg/L)	Source*	Other Cancer Data	Source*
For human and ecological endpoints:							
207-08-9	Benzo(k)fluoranthene	0.0002 mg/L (MCL established for PAH's)	U.S.CFR, 2002	0.001 (13 hr LT50, Daphnia magna)	U.S. EPA, 2002	0.01 (PEF; potency equivalency factor)	U.S.EPA, 1993
16872-11-0	Fluoroboric acid			0.125 mg/L (aquatic concentration of concern, CC)	U.S. EPA 1998a		
16961-83-4	Fluorosilicic acid	430 mg/kg (oral LD50, rat)	RTECS 2003c	N/A			
(a)	Flux A	data withheld for confidentiality					
(a)	Flux B	data withheld for confidentiality					
(a)	Flux D	data withheld for confidentiality					
(a)	Flux E	data withheld for confidentiality					
(a)	Flux F	data withheld for confidentiality					
1309-36-0	Iron pyrite	49.7 mg/m3 (rabbits exhib. damaged tracheal epithelium after 0.5-8 hours inhalation exposure)	Konradova and Bencko, 1975	N/A			
7733-02-0	Zinc sulfate	14.29 mg/kg (oral TDLo for zinc & compounds, human)	RTECS 2003a	4.6 ppm (rainbow trout, 96 hr)	U.S. Coast Guard, 1984-85	3.625 mg/kg (5 day, subcutan; equivocal tumorigenic agent, rabbit)	RTECS 2003a
7440-69-9	Bismuth	0.05 mg/L (0.0014 mg/kg/day in drinking water for 70 kg human)	Ku & Schoenung, 2002	N/A			
For fish LC50 and fish NOEL endpoints only:							
7429-90-5	Aluminum			N/A			
7440-41-7	Beryllium			N/A			
7782-41-4	Fluorine			2.3 ppm (TLm for trout, time not specified)	Weiss 1980		
7782-49-2	Selenium						
7681-52-9	Sodium Hypochlorite			<1.7 mg/L (fish acute toxicity value; <0.02 mg/L CC	U.S. EPA, 1996		
7440-24-6	Strontium			N/A			
7440-62-2	Vanadium			1.8-1.9 (LC50, fathead minnow)	Kimball, n.d.		

Note:
Dark shading indicates data are not needed
* Full citations of sources are provided in the References section of this Appendix (E.3)
(a) Flux material names and CAS#s have been withheld to protect confidentiality

Table E-8. Chemicals used to calculate geometric mean slope factor values for carcinogenic hazard value

Chemical	CAS #	Oral Slope Factor (mg/kg-day)-1	Inhalation Slope Factor (mg/kg-day)-1
Acephate	30560-19-1	8.70E-03	
Acetaldehyde	75-07-0		7.70E-03
Acrylamide	79-06-1	4.50E+00	4.50E+00
Acrylonitrile	107-13-1	5.40E-01	2.40E-01
Alachlor	15972-60-8	8.00E-02	
Aldrin	309-00-2	1.70E+01	1.70E+01
Aniline	62-53-3	5.70E-03	
Aramite	140-57-8	2.50E-02	2.50E-02
Aroclor 1016	12674-11-2	4.00E-01	4.00E-01
Aroclor 1016	12674-11-2	2.00E+00	2.00E+00
Aroclor 1221	11104-28-2	4.00E-01	4.00E-01
Aroclor 1221	11104-28-2	2.00E+00	2.00E+00
Aroclor 1232	11141-16-5	4.00E-01	4.00E-01
Aroclor 1232	11141-16-5	2.00E+00	2.00E+00
Aroclor 1242	53469-21-9	4.00E-01	4.00E-01
Aroclor 1242	53469-21-9	2.00E+00	2.00E+00
Aroclor 1248	12672-29-6	4.00E-01	4.00E-01
Aroclor 1248	12672-29-6	2.00E+00	2.00E+00
Aroclor 1254	11097-69-1	4.00E-01	4.00E-01
Aroclor 1254	11097-69-1		2.00E+00
Aroclor 1260	11096-82-5	4.00E-01	4.00E-01
Aroclor 1260	11096-82-5	2.00E+00	2.00E+00
Arsenic, Inorganic	7440-38-2	1.50E+00	5.00E+01
Atrazine	1912-24-9	2.22E-01	
Azobenzene	103-33-3	1.10E-01	1.10E-01
Benz[a]anthracene	56-55-3	7.30E-01	3.10E-01
Benzene	71-43-2	5.50E-02	2.90E-02
Benzidine	92-87-5	2.30E+02	2.30E+02
Benzo[a]pyrene	50-32-8	7.30E+00	3.10E+00
Benzo[b]fluoranthene	205-99-2	7.30E-01	3.10E-01
Benzo[k]fluoranthene	207-08-9	7.30E-02	3.10E-02
Benzotrichloride	98-07-7	1.30E+01	
Benzyl Chloride	100-44-7	1.70E-01	
Beryllium and compounds	7440-41-7	4.30E+00	8.40E+00
Bis(2-chloro-1-methylethyl)ether (Technical)	108-60-1	7.00E-02	3.50E-02
Bis(2-chloroethyl)ether	111-44-4	1.10E+00	1.10E+00
Bis(2-ethylhexyl)phthalate	117-81-7	1.40E-02	
Bis(chloromethyl)ether	542-88-1	2.20E+02	2.20E+02
Bromodichloromethane	75-27-4	6.20E-02	
Bromoform	75-25-2	7.90E-03	3.90E-03
Butadiene, 1,3-	106-99-0		1.80E+00
Cadmium (Diet)	7440-43-9		6.10E+00
Cadmium (Water)	7440-43-9		6.10E+00
Captafol	2425-06-1	8.60E-03	
Captan	133-06-2	3.50E-03	
Carbazole	86-74-8	2.00E-02	
Carbon Tetrachloride	56-23-5	1.30E-01	5.30E-02
Chloranil	118-75-2	4.03E-01	
Chlordane	057-74-9	3.50E-01	1.30E+00
Chloro-2-methylaniline HCl, 4-	3165-93-3	4.60E-01	
Chloro-2-methylaniline, 4-	95-69-2	5.80E-01	

Table E-8. Chemicals used to calculate geometric mean slope factor values for carcinogenic hazard value

Chemical	CAS #	Oral Slope Factor (mg/kg-day)-1	Inhalation Slope Factor (mg/kg-day)-1
Chlorobenzilate	510-15-6	2.70E-01	2.70E-01
Chlorodibromoethane	73506-94-2	8.40E-02	
Chloroform	67-66-3	6.10E-03	8.10E-02
Chloromethane	74-87-3	1.30E-02	6.30E-03
Chloronitrobenzene, o-	88-73-3	2.50E-02	
Chloronitrobenzene, p-	121-73-3	1.80E-02	
Chlorothalonil	1897-45-6	1.10E-02	
Chromium VI (chromic acid mists)	18540-29-9		4.10E+01
Chromium VI (particulates)	18540-29-9		4.10E+01
Chrysene	218-01-9	7.30E-03	3.10E-03
Coke Oven Emissions	8007-45-2		2.20E+00
Crotonaldehyde, trans-	123-73-9	1.90E+00	
Cyanazine	21725-46-2	8.40E-01	
Cyclohexane, 1,2,3,4,5-pentabromo-6-chloro-	87-84-3	2.30E-02	
DDD	72-54-8	2.40E-01	
DDE	72-55-9	3.40E-01	
DDT	50-29-3	3.40E-01	3.40E-01
Di(2-ethylhexyl)adipate	103-23-1	1.20E-03	
Diallate	2303-16-4	6.10E-02	
Dibenz[a,h]anthracene	53-70-3	7.30E+00	3.10E+00
Dibromo-3-chloropropane, 1,2-	96-12-8	1.40E+00	2.40E-03
Dibromochloromethane	124-48-1	8.40E-02	
Dibromoethane, 1,2-	106-93-4	8.50E+01	7.60E-01
Dichloro-2-butene, 1,4-	764-41-0		9.30E+00
Dichlorobenzene, 1,4-	106-46-7	2.40E-02	
Dichlorobenzidine, 3,3'-	91-94-1	4.50E-01	
Dichloroethane, 1,2-	107-06-2	9.10E-02	9.10E-02
Dichloroethylene, 1,1-	75-35-4	6.00E-01	1.20E+00
Dichloropropane, 1,2-	78-87-5	6.80E-02	
Dichloropropene, 1,3-	542-75-6	1.00E-01	1.40E-02
Dichlorvos	62-73-7	2.90E-01	
Dieldrin	60-57-1	1.60E+01	1.60E+01
Diethylstilbesterol	56-53-1	4.70E+03	4.90E+02
Dimethoxybenzidine, 3,3'-	119-90-4	1.40E-02	
Dimethylaniline HCl, 2,4-	21436-96-4	5.80E-01	
Dimethylaniline, 2,4-	095-68-1	7.50E-01	
Dimethylbenzidine, 3,3'-	119-93-7	9.20E+00	
Dimethylhydrazine, 1,1-	57-14-7	3.00E+00	1.72E+01
Dinitrotoluene Mixture, 2,4/2,6-	25321-14-6	6.80E-01	
Dinitrotoluene, 2,4-	121-14-2	6.80E-01	
Dinitrotoluene, 2,6-	606-20-2	6.80E-01	
Dioxane, 1,4-	123-91-1	1.10E-02	
Diphenylhydrazine, 1,2-	122-66-7	8.00E-01	8.00E-01
Direct Black 38	1937-37-7	8.60E+00	
Direct Blue 6	2602-46-2	8.10E+00	
Direct Brown 95	16071-86-6	9.30E+00	
Epichlorohydrin	106-89-8	9.90E-03	4.20E-03
Ethyl Acrylate	140-88-5	4.80E-02	
Ethylbenzene	100-41-4		3.85E-03
Ethylene Oxide	75-21-8	1.02E+00	3.50E-01
Ethylene Thiourea	96-45-7	1.10E-01	

Table E-8. Chemicals used to calculate geometric mean slope factor values for carcinogenic hazard value

Chemical	CAS #	Oral Slope Factor (mg/kg-day)-1	Inhalation Slope Factor (mg/kg-day)-1
Folpet	133-07-3	3.50E-03	
Fomesafen	72178-02-0	1.90E-01	
Formaldehyde	50-00-0		4.50E-02
Furazolidone	67-45-8	3.80E+00	
Furium	531-82-8	5.00E+01	
Furmecyclox	60568-05-0	3.00E-02	
Heptachlor	76-44-8	4.50E+00	4.50E+00
Heptachlor Epoxide	1024-57-3	9.10E+00	9.10E+00
Hexachlorobenzene	118-74-1	1.60E+00	1.60E+00
Hexachlorobutadiene	87-68-3	7.80E-02	7.80E-02
Hexachlorocyclohexane, Alpha-	319-84-6	6.30E+00	6.30E+00
Hexachlorocyclohexane, Beta-	319-85-7	1.80E+00	1.80E+00
Hexachlorocyclohexane, Gamma-	58-89-9	1.30E+00	
Hexachlorocyclohexane, Technical	608-73-1	1.80E+00	1.80E+00
Hexachlorodibenzo-p-dioxin, Mixture	19408-74-3	6.20E+03	4.55E+03
Hexachloroethane	67-72-1	1.40E-02	1.40E-02
Hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX)	121-82-4	1.10E-01	
HpCDD, 2,3,7,8-	37871-00-4	1.50E+03	1.50E+03
HpCDF, 2,3,7,8-	38998-75-3	1.50E+03	1.50E+03
HxCDD, 2,3,7,8-	34465-46-8	1.50E+04	1.50E+04
HxCDF, 2,3,7,8-	55684-94-1	1.50E+04	1.50E+04
Hydrazine	302-01-2	3.00E+00	1.70E+01
Hydrazine Sulfate	10034-93-2	3.00E+00	1.70E+01
Indeno[1,2,3-cd]pyrene	193-39-5	7.30E-01	3.10E-01
Isophorone	78-59-1	9.50E-04	
Methoxy-5-nitroaniline, 2-	99-59-2	4.60E-02	
Methyl Hydrazine	60-34-4	3.00E+00	1.72E+01
Methyl-5-Nitroaniline, 2-	99-55-8	3.30E-02	
Methylaniline Hydrochloride, 2-	636-21-5	1.80E-01	
Methylene Chloride	75-09-2	7.50E-03	1.65E-03
Methylene-bis(2-chloroaniline), 4,4'-	101-14-4	1.30E-01	1.30E-01
Methylene-bis(N,N-dimethyl) Aniline, 4,4'-	101-61-1	4.60E-02	
Methylenebisbenzenamine, 4,4'-	101-77-9	2.50E-01	
Mirex	2385-85-5	1.80E+00	
Nickel Refinery Dust	NA		8.40E-01
Nickel Subsulfide	12035-72-2		1.70E+00
Nitrofurazone	59-87-0	1.50E+00	
Nitropropane, 2-	79-46-9	9.50E+00	9.40E+00
Nitrosodiethanolamine, N-	1116-54-7	2.80E+00	
Nitrosodiethylamine, N-	55-18-5	1.50E+02	1.50E+02
Nitrosodimethylamine, N-	62-75-9	5.10E+01	5.10E+01
Nitroso-di-N-butylamine, N-	924-16-3	5.40E+00	5.40E+00
Nitroso-di-N-propylamine, N-	621-64-7	7.00E+00	
Nitrosodiphenylamine, N-	86-30-6	4.90E-03	
Nitrosomethylethylamine, N-	10595-95-6	2.20E+01	
Nitroso-N-ethylurea, N-	759-73-9	1.40E+02	
Nitrosopyrrolidine, N-	930-55-2	2.10E+00	2.10E+00
OCDD	3268-87-9	1.50E+02	1.50E+02
OCDF	39001-02-0	1.50E+02	1.50E+02
PeCDD, 2,3,7,8-	36088-22-9	7.50E+04	7.50E+04
PeCDF, 1,2,3,7,8-	57117-41-6	7.50E+04	7.50E+04

Table E-8. Chemicals used to calculate geometric mean slope factor values for carcinogenic hazard value

Chemical	CAS #	Oral Slope Factor (mg/kg-day)-1	Inhalation Slope Factor (mg/kg-day)-1
PeCDF, 2,3,4,7,8-	57117-31-4	7.50E+03	7.50E+03
Pentachloronitrobenzene	82-68-8	2.60E-01	
Pentachlorophenol	87-86-5	1.20E-01	
Phenylenediamine, o-	95-54-5	4.70E-02	
Phenylphenol, 2-	90-43-7	1.94E-03	
Polybrominated Biphenyls	59536-65-1	8.90E+00	
Polychlorinated Biphenyls (high risk)	1336-36-3	2.00E+00	2.00E+00
Polychlorinated Biphenyls (low risk)	1336-36-3	4.00E-01	4.00E-01
Polychlorinated Biphenyls (lowest risk)	1336-36-3	7.00E-02	
Prochloraz	67747-09-5	1.50E-01	
Propylene Oxide	75-56-9	2.40E-01	1.30E-02
Quinoline	91-22-5	1.20E+01	
Simazine	122-34-9	1.20E-01	
Sodium Diethyldithiocarbamate	148-18-5	2.70E-01	
Stirofos (Tetrachlorovinphos)	961-11-5	2.40E-02	
TCDD, 2,3,7,8-	1746-01-6	1.50E+05	1.50E+05
TCDF, 2,3,7,8-	51207-31-9	1.50E+04	1.50E+04
Tetrachloroethane, 1,1,1,2-	630-20-6	2.60E-02	2.60E-02
Tetrachloroethane, 1,1,2,2-	79-34-5	2.00E-01	2.00E-01
Tetrachloroethylene	127-18-4	5.20E-02	2.00E-03
Tetrachlorotoluene, p- alpha, alpha, alpha-	5216-25-1	2.00E+01	
Toluene-2,4-diamine	95-80-7	3.20E+00	
Toluidine, o- (Methylaniline, 2-)	95-53-4	2.40E-01	
Toluidine, p-	106-49-0	1.90E-01	
Toxaphene	8001-35-2	1.10E+00	1.10E+00
Trichloroaniline HCl, 2,4,6-	33663-50-2	2.90E-02	
Trichloroaniline, 2,4,6-	634-93-5	3.40E-02	
Trichloroethane, 1,1,2-	79-00-5	5.70E-02	5.70E-02
Trichloroethylene	79-01-6	1.10E-02	6.00E-03
Trichlorophenol, 2,4,6-	88-06-2	1.10E-02	1.00E-02
Trichloropropane, 1,2,3-	96-18-4	7.00E+00	
Trifluralin	1582-09-8	7.70E-03	
Trimethyl Phosphate	512-56-1	3.70E-02	
Trinitrotoluene, 2,4,6-	118-96-7	3.00E-02	
Vinyl Bromide	593-60-2		1.10E-01
Vinyl Chloride	75-01-4	1.40E+00	3.08E-02
geometric mean		**0.71**	**1.70**
count (n)		**175**	**105**
min		**0.00095**	**0.00165**
max		**150000**	**150000**

blank=no data

Source: Risk Assessment Information System (RAIS), http://risk.lsd.ornl.gov/cgi-bin/tox/TOX_9801 (downloaded 11/00): IRIS/HEAST Slope Factors.

Table E-9. Oral No Observable Adverse Effect Level (NOAEL) data

Chemical	CAS #	Value	unit
2,3,7,8-TCDD	1746-01-6	9E-08	Mg/KgDay
Arsenic	7440-38-2	0.0008	Mg/KgDay
Terbufos	13071-79-9	0.0025	Mg/KgDay
Vanadium	7440-62-2	0.003	Mg/KgDay
Cadmium cmpds	20-04-2	0.005	Mg/KgDay
Manganese oxide	1313-13-9	0.005	Mg/KgDay
Polychlorinated biphenyls	1336-36-3	0.007	Mg/KgDay
Phosphorus (yellow or white)	7723-14-0	0.015	Mg/KgDay
Selenium	7782-49-2	0.015	Mg/KgDay
Phosphine	7803-51-2	0.026	Mg/KgDay
Chloropyrifos	2921-88-2	0.03	Mg/KgDay
Ammonium bifluoride	1341-49-7	0.05	Mg/KgDay
Fluorine	7782-41-4	0.06	Mg/KgDay
Acrylamide	79-06-1	0.1	Mg/KgDay
1,3-Dichloropropene	542-75-6	0.125	Mg/KgDay
Manganese	7439-96-5	0.14	Mg/KgDay
2,4-Dinitrotoluene	121-14-2	0.2	Mg/KgDay
Hexachloro-1,3-butadiene	87-68-3	0.2	Mg/KgDay
Uranium	7440-61-6	0.2	Mg/KgDay
Barium	7440-39-3	0.21	Mg/KgDay
Barium carbonate	513-77-9	0.21	Mg/KgDay
Barium cmpds	20-02-0	0.21	Mg/KgDay
Barium sulfate	7727-43-7	0.21	Mg/KgDay
Bromomethane	74-83-9	0.4	Mg/KgDay
Nitrobenzene	98-95-3	0.46	Mg/KgDay
Hexachlorobenzene	118-74-1	0.5	Mg/KgDay
Copper	7440-50-8	0.53	Mg/KgDay
Lead	7439-92-1	0.57	Mg/KgDay
Cyanazine	21725-46-2	0.625	Mg/KgDay
Trifluralin	1582-09-8	0.75	Mg/KgDay
Zinc (elemental)	7440-66-6	0.9	Mg/KgDay
Acrylonitrile	107-13-1	1	Mg/KgDay
Alachlor	15972-60-8	1	Mg/KgDay
Benzene	71-43-2	1	Mg/KgDay
Carbon tetrachloride	56-23-5	1	Mg/KgDay
Decabromodiphenyl oxide	1163-19-5	1	Mg/KgDay
Hexachloroethane	67-72-1	1	Mg/KgDay
Nitrites	14797-65-0	1	Mg/KgDay
Pyridine	110-86-1	1	Mg/KgDay
Chlorothalonil	1897-45-6	1.5	Mg/KgDay
Nitrate		1.6	Mg/KgDay
Nitrates/nitrites	14797-55-8	1.6	Mg/KgDay
Sodium hypochlorite	7681-52-9	2.1	Mg/KgDay
Chromium (VI)	18540-29-9	2.5	Mg/KgDay
Ethyl dipropylthiocarbamate	759-94-4	2.5	Mg/KgDay
Methyl parathion	298-00-0	2.5	Mg/KgDay
Pentachlorophenol	87-86-5	3	Mg/KgDay
Hydrogen sulfide	7783-06-4	3.1	Mg/KgDay

Table E-9. Oral No Observable Adverse Effect Level (NOAEL) data

Chemical	CAS #	Value	unit
4,4'-Methylenedianiline	101-77-9	3.2	Mg/KgDay
Atrazine	1912-24-9	3.5	Mg/KgDay
1,1,2-Trichloroethane	79-00-5	3.9	Mg/KgDay
Butylate	2008-41-5	5	Mg/KgDay
Hydroquinone	123-31-9	5	Mg/KgDay
Nickel	7440-02-0	5	Mg/KgDay
Nickel chloride	7718-54-9	5	Mg/KgDay
Methyl methacrylate	80-62-6	7.5	Mg/KgDay
1,2,4-Trichlorobenzene	120-82-1	7.8	Mg/KgDay
Boron	7440-42-8	8.8	Mg/KgDay
Carbaryl	63-25-2	9.6	Mg/KgDay
1.4-Dichlorobenzene	106-46-7	10	Mg/KgDay
Maleic anhydride	108-31-6	10	Mg/KgDay
Cyanide (-1)	57-12-5	10.8	Mg/KgDay
Hydrogen cyanide	74-90-8	10.8	Mg/KgDay
Captan	133-06-2	12.5	Mg/KgDay
Chlorobenzene	108-90-7	12.5	Mg/KgDay
Chlorine	7782-50-5	14	Mg/KgDay
Tetrachloroethylene	127-18-4	14	Mg/KgDay
2,4-D	94-75-7	15	Mg/KgDay
Dichlorodifluoromethane	75-71-8	15	Mg/KgDay
Formaldehyde	50-00-0	15	Mg/KgDay
Bromoform	75-25-2	17.9	Mg/KgDay
1,2-Dichloroethane	107-06-2	18	Mg/KgDay
1,2-Dichlorobenzene	95-50-1	18.8	Mg/KgDay
Aluminum hydroxide	21645-51-2	23	Mg/KgDay
Trichloroethylene	79-01-6	24	Mg/KgDay
Maneb	12427-38-2	25	Mg/KgDay
Ethylene oxide	75-21-8	30	Mg/KgDay
N,N-dimethylaniline	121-69-7	32	Mg/KgDay
Ammonia	7664-41-7	34	Mg/KgDay
2-methoxyethanol	109-86-4	50	Mg/KgDay
Acetonitrile	75-05-8	50	Mg/KgDay
Biphenyl	92-52-4	50	Mg/KgDay
Chlorophenols [o]	20-05-3	50	Mg/KgDay
Di (2-ethylhexyl) phthalate	117-81-7	50	Mg/KgDay
Methyl isobutyl ketone	108-10-1	50	Mg/KgDay
P-cresol	106-44-5	50	Mg/KgDay
Aluminum (elemental)	7429-90-5	60	Mg/KgDay
Phenol	108-95-2	60	Mg/KgDay
Boric acid	11113-50-1	67	Mg/KgDay
Orthoboric acid	10043-35-3	67	Mg/KgDay
4-Nitrophenol	100-02-7	70	Mg/KgDay
Coolant	not available	71	Mg/KgDay
Ethylene glycol	107-21-1	71	Mg/KgDay
Naphthalene	91-20-3	71	Mg/KgDay
Butyraldehyde	123-72-8	75	Mg/KgDay
Diethanolamine	111-42-2	75	Mg/KgDay

Table E-9. Oral No Observable Adverse Effect Level (NOAEL) data

Chemical	CAS #	Value	unit
Pyrene	129-00-0	75	Mg/KgDay
Acrylic acid	79-10-7	83	Mg/KgDay
Butyl acrylate	141-32-2	84	Mg/KgDay
Acetone	67-64-1	100	Mg/KgDay
Methyl tert-butyl ether	1634-04-4	100	Mg/KgDay
Nickel cmpds	20-14-4	100	Mg/KgDay
Styrene	100-42-5	100	Mg/KgDay
Toluene	108-88-3	100	Mg/KgDay
Vinyl acetate	108-05-4	100	Mg/KgDay
Acetaldehyde	75-07-0	125	Mg/KgDay
Dibutyl phthalate	84-74-2	125	Mg/KgDay
Fluoranthene	206-44-0	125	Mg/KgDay
Fluorene	86-73-7	125	Mg/KgDay
Methyl ethyl ketone	78-93-3	125	Mg/KgDay
N-butyl alcohol	71-36-3	125	Mg/KgDay
Ethylbenzene	100-41-4	136	Mg/KgDay
Benzaldehyde	100-52-7	143	Mg/KgDay
Diethyl phthalate	84-66-2	150	Mg/KgDay
Isophorone	78-59-1	150	Mg/KgDay
Butyl benzyl phthalate	85-68-7	151	Mg/KgDay
Cumene	98-82-8	154	Mg/KgDay
Dichloromethane	75-09-2	155	Mg/KgDay
Acenaphthene	83-32-9	175	Mg/KgDay
m, p-xylene	1330-20-7	179	Mg/KgDay
o-xylene	95-47-6	179	Mg/KgDay
Xylene (mixed isomers)	1330-20-7	179	Mg/KgDay
Strontium	7440-24-6	190	Mg/KgDay
Strontium carbonate	1633-05-2	190	Mg/KgDay
Acetic acid	64-19-7	195	Mg/KgDay
Dioctyl sebacate	122-62-3	200	Mg/KgDay
Propylene oxide	75-56-9	200	Mg/KgDay
Glycol ethers	111-76-2	203	Mg/KgDay
Isopropyl alcohol	67-63-0	230	Mg/KgDay
1,1,1-Trichloroethane	71-55-6	250	Mg/KgDay
1,2-Dichloropropane	78-87-5	250	Mg/KgDay
2-ethoxyethanol	110-80-5	250	Mg/KgDay
m-xylene	108-38-3	250	Mg/KgDay
1,2-Dichlorotetrafluoroethane	76-14-2	273	Mg/KgDay
Freon 113	76-13-1	273	Mg/KgDay
Metolachlor	51218-45-2	300	Mg/KgDay
Ethanol amine	141-43-5	320	Mg/KgDay
Acetophenone	98-86-2	423	Mg/KgDay
Di propylene glycol butyl ether	29911-28-2	450	Mg/KgDay
4,4'-Isopropylidenediphenol	80-05-7	500	Mg/KgDay
Diethyl ether	60-29-7	500	Mg/KgDay
Methanol	67-56-1	500	Mg/KgDay
Terephthalic acid	100-21-0	500	Mg/KgDay
Polyvinyl pyrrolidone (PVP)	9003-39-8	550	Mg/KgDay

Table E-9. Oral No Observable Adverse Effect Level (NOAEL) data

Chemical	**CAS #**	**Value**	**unit**
Bis (2-ethylhexyl) adipate	103-23-1	610	Mg/KgDay
Tetrahydrofuran	109-99-9	782	Mg/KgDay
Glyphosate	1071-83-6	800	Mg/KgDay
2-(2-butoxyethoxy)-ethanol acetate	124-17-4	1000	Mg/KgDay
Anthracene	120-12-7	1000	Mg/KgDay
Dimethyl phthalate	131-11-3	1000	Mg/KgDay
Heptane	142-82-5	1000	Mg/KgDay
p-xylene	106-42-3	1000	Mg/KgDay
Phosphate ester	57583-54-7	1000	Mg/KgDay
Polyethylene mono (nonylphenyl) ether glycol	9016-45-9	1000	Mg/KgDay
Diethylene glycol	111-46-6	1250	Mg/KgDay
Chromium (III)	16065-83-1	1468	Mg/KgDay
Chromium trioxide	1333-82-0	1468	Mg/KgDay
Tert-butyl alcohol	75-65-0	1599	Mg/KgDay
Bismuth	7440-69-9	3243	Mg/KgDay
Zirconium	7440-67-7	3494	Mg/KgDay
	Count n=	160	
	geometric mean=	13.987	
	minumum=	9E-08	
	maximum=	3494	

Table E-10. Inhalation No Observable Adverse Effect Level (NOAEL)

Chemical	CAS #	Value	unit
1,1,1-Trichloroethane	71-55-6	1214.9	mg/m3
1,2,4-Trichlorobenzene	120-82-1	24.3	mg/m3
1,2-Dichloroethane	107-06-2	221	mg/m3
1,2-Dichloropropane	78-87-5	710	mg/m3
1,3-Butadiene	106-99-0	2800	mg/m3
1,3-Dichloropropene	542-75-6	49.6	mg/m3
1,4-Dichlorobenzene	106-46-7	75	mg/m3
1,4-Dioxane	123-91-1	360	mg/m3
1-Methoxy-2-propanol	107-98-2	658	mg/m3
2-Ethoxyethanol	110-80-5	7480	mg/m3
2-Methoxyethanol	109-86-4	93.3	mg/m3
4,4'-Isopropylidenediphenol	80-05-7	10	mg/m3
4-Nitrophenol	100-02-7	30	mg/m3
Acetaldehyde	75-07-0	300	mg/m3
Acetonitrile	75-05-8	91.5	mg/m3
Acrylic acid	79-10-7	74	mg/m3
Allyl chloride	107-05-1	68.3	mg/m3
Ammonia	7664-41-7	40	mg/m3
Ammonium nitrate (solution)	6484-52-2	185	mg/m3
Aniline	62-53-3	19	mg/m3
Benzene	71-43-2	1.15	mg/m3
Bromomethane	74-83-9	4.3	mg/m3
Butyl acrylate	141-32-2	120	mg/m3
Butyl benzyl phthalate	85-68-7	144	mg/m3
Butyraldehyde	123-72-8	3200	mg/m3
Carbon disulfide	75-15-0	10	mg/m3
Carbon monoxide	630-08-0	114.5	mg/m3
Carbon tetrachloride	56-23-5	34.3	mg/m3
Chlorobenzene	108-90-7	377	mg/m3
Coolant	not available	10	mg/m3
Cumene	98-82-8	537	mg/m3
Cumene hydroperoxide	80-15-9	31	mg/m3
Cyclohexane	110-82-7	1500	mg/m3
Di (2-ethylhexyl) phthalate	117-81-7	50	mg/m3
Dichlorobenzene (mixed isomers)	25321-22-6	610.4	mg/m3
Dichloromethane	75-09-2	796	mg/m3
Diethanolamine	111-42-2	0.27	mg/m3
Epichlorohydrin	106-89-8	20.7	mg/m3
Ethyl chloride	75-00-3	3600	mg/m3
Ethylbenzene	100-41-4	2370	mg/m3
Ethylene	74-85-1	11600	mg/m3
Ethylene glycol	107-21-1	10	mg/m3
Ethylene oxide	75-21-8	18	mg/m3
Formaldehyde	50-00-0	0.6	mg/m3
Glycol ethers	111-76-2	121	mg/m3
HCFC-22	75-45-6	5260	mg/m3
Hexachloro-1,3-butadiene	87-68-3	58.2	mg/m3
HFC-125	354-33-6	245000	mg/m3
Hydrochloric acid	7647-01-0	15	mg/m3
Isopropyl alcohol	67-63-0	268.3	mg/m3
Maneb	12427-38-2	10	mg/m3

Table E-10. Inhalation No Observable Adverse Effect Level (NOAEL)

Chemical	CAS #	Value	unit
Mercury	7439-97-6	0.006	mg/m3
Methanol	67-56-1	130	mg/m3
Methyl chloride	74-87-3	1138.4	mg/m3
Methyl ethyl ketone	78-93-3	8047	mg/m3
Methyl isobutyl ketone	108-10-1	224	mg/m3
Methyl methacrylate	80-62-6	111.7	mg/m3
Metyl tert-butyl ether	1634-04-4	2880	mg/m3
N,N-Dimethylaniline	121-69-7	0.006	mg/m3
N-butyl alcohol	71-36-3	0.1	mg/m3
Nitrobenzene	98-95-3	27.5	mg/m3
p-cresol	106-44-5	10	mg/m3
p-xylene	106-42-3	5812.6	mg/m3
Phosphine	7803-51-2	0.25	mg/m3
Phosphoric acid	7664-38-2	50	mg/m3
Propionaldehyde	123-38-6	200	mg/m3
Propylene	115-07-1	9375	mg/m3
Propylene glycol	57-55-6	170	mg/m3
Propylene oxide	75-56-9	237	mg/m3
Sec-butyl alcohol	78-92-2	8270	mg/m3
Styrene	100-42-5	565	mg/m3
Sulfur dioxide	7446-09-5	0.104	mg/m3
Sulfuric acid	7664-93-9	0.1	mg/m3
Terephthalic acid	100-21-0	3	mg/m3
Tetrachloroethylene	127-18-4	740.2	mg/m3
Tetrahydrofuran	109-99-9	0.2	mg/m3
Titanium	7440-32-6	0.8	mg/m3
Titanium tetrachloride	7550-45-0	0.009	mg/m3
Toluene	108-88-3	411.1	mg/m3
Toluene-2,4-diisocyanate	584-84-9	0.03	mg/m3
Trichloroethylene	79-01-6	586.6	mg/m3
Vinyl acetate	108-05-4	176	mg/m3
Vinyl chloride	75-01-4	69754.5	mg/m3
Vinylidene chloride	75-35-4	120	mg/m3
	Count n=	84	
	Geometric mean=	68.6653	
	minimum=	0.006	
	maximum=	245000	

Table E-11. Fish Lethal Concentration to 50 percent of exposed population (LC_{50})

Chemical	CAS #	Value	unit
1,1,1-Trichloroethane	71-55-6	48	mg/L
1,1,2-Trichloroethane	79-00-5	82	mg/L
1,2,3,5-Tetrachlorobenzene	634-90-2	4	mg/L
1,2,4-Trichlorobenzene	120-82-1	3	mg/L
1,2,4-Trimethylbenzene	95-63-6	8	mg/L
1,2-Dichlorobenzene	95-50-1	1	mg/L
1,2-Dichloroethane	107-06-2	136	mg/L
1,2-Dichloropropane	78-87-5	127	mg/L
1,3-Butadiene	106-99-0	4	mg/L
1,3-Dichloropropene	542-75-6	0.24	mg/L
1,4-Dichlorobenzene	106-46-7	34	mg/L
1,4-Dioxane	123-91-1	9850	mg/L
1-Methylphenanthrene	832-69-9	1	mg/L
2,4,5-Trichlorotoluene	6639-30-1	1	mg/L
2,4,6-Trichlorophenol	88-06-2	3	mg/L
2,4-D	94-75-7	71	mg/L
2,4-Dinitrophenol	51-28-5	11	mg/L
2,4-Dinitrotoluene	121-14-2	24	mg/L
2-Ethoxyethanol	110-80-5	16305	mg/L
2-Methoxyethanol	109-86-4	22655	mg/L
2-Nitropropane	79-46-9	5	mg/L
3,4-Dinitrotoluene	610-39-9	2	mg/L
4,4'-Isopropylidenediphenol	80-05-7	5	mg/L
4,4'-Methylenedianiline	101-77-9	45	mg/L
4-Nitrophenol	100-02-7	41	mg/L
Acetaldehyde	75-07-0	34	mg/L
Acetone	67-64-1	7200	mg/L
Acetonitrile	75-05-8	1640	mg/L
Acrylamide	79-06-1	109	mg/L
Acrylic acid	79-10-7	186	mg/L
Acrylonitrile	107-13-1	10	mg/L
Alachlor	15972-60-8	5	mg/L
Allyl chloride	107-05-1	72	mg/L
Aluminum	7429-90-5	11	mg/L
Aluminum (+3)		3.6	mg/L
Ammonia	7664-41-7	2	mg/L
Ammonium nitrate (solution)	6484-52-2	800	mg/L
Ammonium sulfate (solution)	7783-20-2	4000	mg/L
Aniline	62-53-3	108	mg/L
Anthracene	120-12-7	0.01	mg/L
Antimony	7440-36-0	14.4	mg/L
Antimony cmpds	20-00-8	833	mg/L
Arsenic	7440-38-2	14.4	mg/L
Arsenic cmpds	20-01-9	32	mg/L
Atrazine	1912-24-9	16	mg/L
Barium	7440-39-3	580	mg/L
Barium cmpds	20-02-0	200	mg/L
Benzaldehyde	100-52-7	27	mg/L
Benzene	71-43-2	19	mg/L
Benzoyl chloride	98-88-4	35	mg/L

Table E-11. Fish Lethal Concentration to 50 percent of exposed population (LC_{50})

Chemical	CAS #	Value	unit
Beryllium	7440-90-5	2	mg/L
Biphenyl	92-52-4	2	mg/L
Bis(2-ethylhexyl) adipate	103-23-1	0.35	mg/L
Boron	7440-42-8	113	mg/L
Boron (B III)		113	mg/L
Bromomethane	74-83-9	11	mg/L
Butyl benzyl phthalate	85-68-7	43	mg/L
Butylate	2008-41-5	7	mg/L
Butyraldehyde	123-72-8	32	mg/L
Cadmium	7440-43-9	0.001	mg/L
Cadmium cmpds	20-04-2	0.1	mg/L
Caffeine	58-08-2	151	mg/L
Captan	133-06-2	0.2	mg/L
Carbaryl	63-25-2	8	mg/L
Carbon disulfide	79-15-0	694	mg/L
Carbon tetrachloride	56-23-5	41	mg/L
Carbonyl sulfide	463-58-1	2685	mg/L
Catechol	120-80-9	9	mg/L
Chlorine	7782-50-5	0.34	mg/L
Chlorine dioxide	10049-04-4	0.17	mg/L
Chlorobenzene	108-90-7	17	mg/L
Chloroform	67-66-3	71	mg/L
Chlorophenols [o]	20-05-3	19	mg/L
Chloroprene	126-99-8	2	mg/L
Chlorothalonil	1897-45-6	0.05	mg/L
Chlorpyrifos	2921-88-2	2.4	mg/L
Chromium	7440-47-3	52	mg/L
Chromium (VI)	18540-29-9	22.6	mg/L
Chromium cmpds	20-06-4	33	mg/L
Chromium III	16065-83-1	3.3	mg/L
Cobalt cmpds	20-07-5	0.38	mg/L
Coolant		227634	mg/L
Copper	7440-50-8	0.014	mg/L
Copper (+1 & +2)		0.014	mg/L
Copper cmpds	20-08-6	0.33	mg/L
Cresol (mixed isomers)	1319-77-3	13	mg/L
Cumene	98-82-8	6	mg/L
Cumene hydroperoxide	80-15-9	62	mg/L
Cyanazine	21725-46-2	18	mg/L
Cyanide (-1)	57-12-5	56	mg/L
Cyclohexane	110-82-7	5	mg/L
Cyclohexanone	108-94-1	630	mg/L
Cyclohexylamine	108-91-8	222	mg/L
Decabromodiphenyl oxide	1163-19-5	0.06	mg/L
Di (2-ethylhexyl)phthalate	117-81-7	1	mg/L
Diaminotoluene (mixed isomers)	25376-45-8	37	mg/L
Dibutyl phthalate	84-74-2	1	mg/L
Dichlorobenzene (mixed isomers)	25321-22-6	1	mg/L
Dichloromethane	75-09-2	330	mg/L
Diethanolamine	111-42-2	4710	mg/L

Table E-11. Fish Lethal Concentration to 50 percent of exposed population (LC_{50})

Chemical	CAS #	Value	unit
Diethyl phthalate	84-66-2	32	mg/L
Dimethyl phthalate	131-11-3	121	mg/L
Di-n-octyl phthalate	117-84-0	1	mg/L
Edetic acid (EDTA)	60-00-4	473	mg/L
Epichlorohydrin	106-89-8	35	mg/L
Ethyl chloride	75-00-3	16	mg/L
Ethyl dipropylthiocarbamate	759-94-4	27	mg/L
Ethylbenzene	100-41-4	11	mg/L
Ethylene	74-85-1	14	mg/L
Ethylene glycol	107-21-1	227634	mg/L
Ethylene oxide	75-21-8	84	mg/L
Fluorine	7782-49-2	100	mg/L
Formaldeyde	50-00-0	24	mg/L
Freon 113	76-13-1	290	mg/L
Glycol ethers	111-76-2	1490	mg/L
Glyphosate	1071-83-6	600	mg/L
Hexachloro-1,3-butadiene	87-68-3	0.09	mg/L
Hexachlorobenzene	118-74-1	22	mg/L
Hexachlorocyclopentadiene	77-47-4	0.007	mg/L
Hexachloroethane	67-72-1	1	mg/L
Hexane	110-54-3	2.5	mg/L
Hydrazine	302-01-2	4.83	mg/L
Hydrochloric acid	7647-01-0	19	mg/L
Hydrofluoric acid	7664-39-3	265	mg/L
Hydrogen cyanide	74-90-8	1385	mg/L
Hydroquinone	123-31-9	141	mg/L
Isobutyraldehyde	78-84-2	41	mg/L
Isopropyl alcohol	67-63-0	8623	mg/L
Lead	7439-92-1	31.5	mg/L
Lead cmpds	20-11-1	5	mg/L
Lead sulfate cake	7446-14-2	60.8	mg/L
Lithium salts		2600	mg/L
M,p-xylene		13	mg/L
Malathion	121-75-5	0.1	mg/L
Maleic anhydride	108-31-6	2963	mg/L
Maneb	12427-38-2	2	mg/L
Manganese cmpds	20-12-2	150	mg/L
Mercury	7439-97-6	0.155	mg/L
Mercury cmpds		0.155	mg/L
Metam sodium	137-42-8	0.39	mg/L
Methanol	67-56-1	29400	mg/L
Methl mercury	115-09-3	0.09	mg/L
Methyl chloride	74-87-3	550	mg/L
Methyl ethyl ketone	78-93-3	3220	mg/L
Methyl isobutyl ketone	108-10-1	505	mg/L
Methyl methacrylate	80-62-6	259	mg/L
Methyl parathion	298-00-0	9	mg/L
Methyl tert-butyl ether	1634-04-4	786	mg/L
Methylenebis (phenylisocyanate)	101-68-8		mg/L
Metolachlor	51218-45-2	15	mg/L

Table E-11. Fish Lethal Concentration to 50 percent of exposed population (LC_{50})

Chemical	CAS #	Value	unit
Metribuzin	21087-64-9	80	mg/L
Molybdenum	7439-98-7	157	mg/L
Molybdenum (Mo II, Mo III, Mo IV, Mo V, Mo VI)		157	mg/L
Molybdenum trioxide	1313-27-5	370	mg/L
m-xylene	108-38-3	16	mg/L
N, N-Demethylaniline	121-69-7	65	mg/L
Naphthalene	91-20-3	6	mg/L
N-butyl alcohol	71-36-3	1860	mg/L
Nickel	7440-02-0	2.48	mg/L
Nickel cmpds	20-14-4	27	mg/L
Nitrate		2213	mg/L
Nitrates/nitrites	14797-55-8	2213	mg/L
Nitric acid	7697-37-2	26	mg/L
Nitrites	14797-65-0	225	mg/L
Nitrobenzene	98-95-3	119	mg/L
Nitrogen dioxide	10102-44-0	196	mg/L
N-nitrosodiphenylamine	86-30-6	1	mg/L
o-xylene	95-47-6	16	mg/L
p-cresol	106-44-5	25	mg/L
Phenol	108-95-2	34	mg/L
Phosphoric acid	7664-38-2	70	mg/L
Phosphorus (yellow or white)	7723-14-0	0.02	mg/L
Phthalic anhydride	85-44-9	364	mg/L
Picric acid	88-89-1	170	mg/L
Polychlorinated biphenyls	1336-36-3	3	mg/L
Propionaldehyde	123-38-6	44	mg/L
Propylene	115-07-1	5	mg/L
Propylene oxide	75-56-9	306	mg/L
p-xylene	106-42-3	2	mg/L
Pyridine	110-86-1	100	mg/L
Sec-butyl alcohol	78-92-2	3670	mg/L
Selenium	7782-49-2	4.9	mg/L
Silver	7440-22-4	0.004	mg/L
Silver cmpds		12	mg/L
Silvex	93-72-1	13	mg/L
Sodium Hypochlorite	7681-52-9	0.53	mg/L
Strontium	7440-24-6	210	mg/L
Styrene	100-42-5	4	mg/L
Sulfuric acid	7664-93-9	31	mg/L
Terbufos	13071-79-9	0.01	mg/L
Terephthalic acid	100-21-0	29	mg/L
Tert-butyl alcohol	75-65-0	1954	mg/L
Tetrachloroethylene	127-18-4	17	mg/L
Tin	7440-31-5	626	mg/L
Tin (Sn++, Sn4+)		626	mg/L
Titanium tetrachloride	7550-45-0	25	mg/L
Toluene	108-88-3	34	mg/L
Toluene-2,4-diisocyanate	584-84-9	53	mg/L
Trans-1,2-dichloroethylene	156-60-5	45	mg/L
Trichloroethylene	79-01-6	44	mg/L

Table E-11. Fish Lethal Concentration to 50 percent of exposed population (LC_{50})

Chemical	CAS #	Value	unit
Trichlorofluoromethane	75-69-4	114	mg/L
Triethylene glycol	112-27-6	88100	mg/L
Trifluralin	1582-09-8	0.11	mg/L
Vanadium	7440-62-2	4	mg/L
Vinyl acetate	108-05-4	100	mg/L
Vinyl chloride	75-01-4	143	mg/L
Vinylidene chloride	75-35-4	108	mg/L
Xylene (mixed isomers)	1330-20-7	13	mg/L
Zinc (+2)		0.09	mg/L
Zinc (elemental)	7440-66-6	0.09	mg/L
Zinc cmpds	20-19-9	17	mg/L
Benzo(k)fluoranthene	207-08-9	1000	mg/L
Beta terpineol	138-87-4	5.4	mg/L
Di propylene glycol butyl ether	29911-28-2	930	mg/L
2,2-Dimethylolpropionic acid	4767-03-7	1000	mg/L
Ethoduomeen	53127-17-6	0.5	mg/L
Fluoroboric acid	16872-11-0	1000	mg/L
Fluorosilicic acid	16961-83-4	100	mg/L
Iron pyrite	1309-36-0	1000	mg/L
Tri propylene glycol butyl ether	55934-93-5	900	mg/L
Zinc sulfate	7733-02-0	14	mg/L
Bismuth	7440-69-9	5	mg/L
	Count n=	221	
	Geometric mean=	24.592	
	minimum=	0.001	
	maximum=	227634	

Table E-12. Fish No Observed Effect Level (NOEL)

Chemical	CAS #	Value	unit
1,1,1-Trichloroethane	71-55-6	7	mg/L
1,1,2-Trichloroethane	79-00-5	1	mg/L
1,2,4-Trichlorobenzene	120-82-1	0.2	mg/L
1,2,4-Trimethylbenzene	95-63-6	0.68	mg/L
1,2-Dichlorobenzene	95-50-1	0.05	mg/L
1,2-Dichloroethane	107-06-2	34	mg/L
1,2-Dichloropropane	78-87-5	23	mg/L
1,3-Butadiene	106-99-0	1	mg/L
1,3-Dichloropropene	542-75-6	0.06	mg/L
1,4-Dichlorobenzene	106-46-7	3	mg/L
1,4-Dioxane	123-91-1	2588	mg/L
2,4-D	94-75-7	6	mg/L
2,4-Dinitrophenol	51-28-5	3	mg/L
2,4-Dinitrotoluene	121-14-2	6	mg/L
2-Ethoxyethanol	110-80-5	4076	mg/L
2-Methoxyethanol	109-86-4	5664	mg/L
2-Nitropropane	79-46-9	1	mg/L
4,4'-Isopropylidenediphenol	80-05-7	0.42	mg/L
4,4'-Methylenedianiline	101-77-9	11	mg/L
4-Nitrophenol	100-02-7	10	mg/L
Acetaldehyde	75-07-0	9	mg/L
Acetone	67-64-1	1800	mg/L
Acetonitrile	75-05-8	410	mg/L
Acrylamide	79-06-1	27	mg/L
Acrylic acid	79-10-7	47	mg/L
Acrylonitrile	107-13-1	3	mg/L
Alachlor	15972-60-8	0.51	mg/L
Allyl chloride	107-05-1	18	mg/L
Aluminum (+3)		0.36	mg/L
Ammonia	7664-41-7	0.09	mg/L
Ammonium nitrate (solution)	6484-52-2	40	mg/L
Ammonium sulfate (solution)	7783-20-2	200	mg/L
Aniline	62-53-3	27	mg/L
Antimony	7440-36-0	1.6	mg/L
Antimony cmpds	20-00-8	42	mg/L
Arsenic	7440-38-2	2.1	mg/L
Arsenic cmpds	20-01-9	2	mg/L
Atrazine	1912-24-9	3	mg/L
Barium	7440-39-3	50	mg/L
Barium cmpds	20-02-0	10	mg/L
Benzene	71-43-2	4	mg/L
Benzoyl chloride	98-88-4	9	mg/L
Biphenyl	92-52-4	0.12	mg/L
Bis (2-ethylhexyl)adipate	103-23-1	0.09	mg/L
Boron	7440-42-8	27	mg/L
Boron (B III)		27	mg/L
Bromomethane	74-83-9	3	mg/L
Butyl acrylate	141-32-2	0.31	mg/L
Butyl benzyl phthalate	85-68-7	2	mg/L

Table E-12. Fish No Observed Effect Level (NOEL)

Chemical	CAS #	Value	unit
Butylate	2008-41-5	2	mg/L
Butyraldehyde	123-72-8	8	mg/L
Cadmium	7440-43-9	0.001	mg/L
Captan	133-06-2	0.05	mg/L
Carbaryl	63-25-2	1	mg/L
Carbon disulfide	75-15-0	174	mg/L
Carbon tetrachloride	56-23-5	5	mg/L
Carbonyl sulfide	463-58-1	671	mg/L
Catechol	120-80-9	2	mg/L
Chlorine	7782-50-5	0.02	mg/L
Chlorine dioxide	10049-04-4	0.01	mg/L
Chlorobenzene	108-90-7	2	mg/L
Chloroform	67-66-3	18	mg/L
Chlorophenols [o]	20-05-3	3	mg/L
Chloroprene	126-99-8	0.56	mg/L
Chlorothalonil	1897-45-6	0.01	mg/L
Chlorpyrifos	2921-88-2	0.12	mg/L
Chromium	7440-47-3	5.2	mg/L
Chromium III	16065-83-1	0.33	mg/L
Chromium VI	18540-29-9	2.23	mg/L
Chromium cmpds	20-06-4	2	mg/L
Cobalt cmpds	20-07-5	0.02	mg/L
Coolant	not available	56909	mg/L
Copper	7440-50-8	0.004	mg/L
Copper (+1 & +2)		0.004	mg/L
Copper cmpds	20-08-6	0.02	mg/L
Cresol (mixed isomers)	1319-77-3	3	mg/L
Cumene	92-82-8	0.49	mg/L
Cumene hydroperoxide	80-15-9	16	mg/L
Cyanazine	21725-46-2	5	mg/L
Cyanide (-1)	57-12-5	5.7	mg/L
Cyclohexane	110-82-7	0.39	mg/L
Di (2-ethylhexyl) phthalate	117-81-7	0.08	mg/L
Di-n-octyl phthalate	117-84-0	0.05	mg/L
Diaminotoluene (mixed isomers)	25376-45-8	9	mg/L
Dibutyl phthalate	84-74-2	0.05	mg/L
Dichlorobenzene (mixed isomers)	25321-22-6	0.05	mg/L
Dichloromethane	75-09-2	83	mg/L
Diethanolamine	111-42-2	1178	mg/L
Diethyl phthalate	84-66-2	5	mg/L
Dimethyl phthalate	131-11-3	30	mg/L
Edetic acid (EDTA)	60-00-4	240	mg/L
Epichlorohydrin	106-89-8	9	mg/L
Ethoduomeen	53127-17-6	0.05	mg/L
Ethyl chloride	75-00-3	4	mg/L
Ethyl dipropylthiocarbamate	759-94-4	3	mg/L
Ethylbenzene	100-41-4	1	mg/L
Ethylene	74-85-1	3	mg/L
Ethylene glycol	107-21-1	56909	mg/L

Table E-12. Fish No Observed Effect Level (NOEL)

Chemical	CAS #	Value	unit
Ethylene oxide	75-21-8	118	mg/L
Formaldehyde	50-00-0	6	mg/L
Freon 113	76-13-1	73	mg/L
Glycol ethers	111-76-2	373	mg/L
Glyphosate	1071-83-6	150	mg/L
Hexachlorobenzene	118-74-1	1	mg/L
Hexachloroethane	67-72-1	0.35	mg/L
Hexane	110-54-3	0.25	mg/L
Hydrazine	302-01-2	0.48	mg/L
Hydrochloric acid	7647-01-0	0.95	mg/L
Hydrofluoric acid	7664-39-3	13	mg/L
Hydrogen cyanide	74-90-8	346	mg/L
Hydroquinone	123-31-9	35	mg/L
Isobutyraldehyde	78-84-2	10	mg/L
Isopropyl alcohol	67-63-0	2156	mg/L
Lead	7439-92-1	0.004	mg/L
Lead cmpds	20-11-1	0.26	mg/L
Lead sulfate cake	7446-14-2	6.08	mg/L
Lithium salts		260	mg/L
M,p-xylene	1330-20-7	1	mg/L
m-xylene	108-38-3	2	mg/L
Malathion	121-75-5	0.01	mg/L
Maleic anhydride	108-31-6	741	mg/L
Maneb	12427-38-2	0.09	mg/L
Manganese cmpds	20-12-2	8	mg/L
Mercury	7439-97-6	0.005	mg/L
Mercury cmpds	not applicable	0.005	mg/L
Metam sodium	137-42-8	0.1	mg/L
Methanol	67-56-1	7350	mg/L
Methyl chloride	74-87-3	138	mg/L
Methyl ethyl ketone	78-93-3	805	mg/L
Methyl isobutyl ketone	108-10-1	126	mg/L
Methyl methacrylate	80-62-6	65	mg/L
Methyl parathion	298-00-0	0.88	mg/L
Methyl tert-butyl ether	1634-04-4	197	mg/L
Methylenebis (phenylisocyanate)	101-68-8	16	mg/L
Metolachlor	51218-45-2	1	mg/L
Metribuzin	21087-64-9	20	mg/L
Molybdenum	7439-98-7	0.125	mg/L
Molybdenum (Mo II, Mo III, Mo IV, Mo V, Mo VI)		0.125	mg/L
Molybdenum trioxide	1313-27-5	19	mg/L
N,N-Dimethylaniline	121-69-7	12	mg/L
N-butyl alcohol	71-36-3	465	mg/L
N-nitrosodiphenylamine	86-30-6	0.13	mg/L
Naphthalene	91-20-3	0.59	mg/L
Nickel	7440-02-0	0.09	mg/L
Nickel cmpds	20-14-4	1	mg/L
Nitrate		213	mg/L
Nitrates/nitrites	14797-55-8	213	mg/L

Table E-12. Fish No Observed Effect Level (NOEL)

Chemical	CAS #	Value	unit
Nitric acid	7697-37-2	1	mg/L
Nitrobenzene	98-95-3	30	mg/L
Nitrogen dioxide	10102-44-0	19.6	mg/L
o-xylene	95-47-6	2	mg/L
p-cresol	106-44-5	6	mg/L
p-xylene	106-42-3	0.2	mg/L
Phenol	108-95-2	8	mg/L
Phosphoric acid	7664-38-2	4	mg/L
Phthalic anhydride	85-44-9	91	mg/L
Picric acid	88-89-1	41	mg/L
Polychlorinated biphenyls	1336-36-3	0.14	mg/L
Propionaldehyde	123-38-6	11	mg/L
Propylene	115-07-1	1	mg/L
Propylene oxide	75-56-9	77	mg/L
Pyridine	110-86-1	25	mg/L
Sec-butyl alcohol	78-92-2	918	mg/L
Silver	7440-22-4	0.001	mg/L
Silver cmpds		0.001	mg/L
Styrene	100-42-5	0.44	mg/L
Sulfuric acid	7664-93-9	2	mg/L
Terephthalic acid	100-21-0	7	mg/L
Tert-butyl alcohol	75-65-0	488	mg/L
Tetrachloroethylene	127-18-4	2	mg/L
Tin	7440-31-5	62.6	mg/L
Tin (Sn++, Sn4+)		62.6	mg/L
Titanium tetrachloride	7550-45-0	1	mg/L
Toluene	108-88-3	4	mg/L
Toluene-2,4-diisocyanate	584-84-9	13	mg/L
Trichloroethylene	79-01-6	8	mg/L
Triethylene glycol	112-27-6	8810	mg/L
Trifluralin	1582-09-8	0.01	mg/L
Vinyl acetate	108-05-4	25	mg/L
Vinyl chloride	75-01-4	36	mg/L
Vinylidene chloride	75-35-4	27	mg/L
Xylene (mixed isomers)	1330-20-7	1	mg/L
Zinc (+2)		0.036	mg/L
Zinc (elemental)	7440-66-6	0.036	mg/L
Benzo(k)fluoranthene	207-08-9	0.006	mg/L
Beta terpineol	138-87-4	0.87	mg/L
Di propylene glycol butyl ether	29911-28-2	100	mg/L
2,2-Dimethylolpropionic acid (DMPA)	4767-03-7	100	mg/L
Fluorosilicic acid	16961-83-4	10	mg/L
Iron pyrite	1309-36-0	100	mg/L
Tri propylene glycol butyl ether	55934-93-5	90	mg/L
Zinc sulfate	7733-02-0	0.8	mg/L
Fluoroboric acid	16872-11-0	20	mg/L
Bismuth	7440-69-9	0.5	mg/L
Aluminum	7429-90-5	3.3	mg/L
Beryllium	7440-41-7	0.2	mg/L
Fluorine	7782-41-4	10	mg/L

Table E-12. Fish No Observed Effect Level (NOEL)

Chemical	CAS #	Value	unit
Selenium	7782-49-2	0.1	mg/L
Sodium hypochlorite	7681-52-9	0.05	mg/L
Strontium	7440-24-6	20	mg/L
Vanadium	7440-62-2	0.67	mg/L
	Count n=	199	
Geometric mean=		3.9012	
	minimum=	0.001	
	maximum=	56909	

Table E-13. Geometric means used to calculate toxicity hazard values [a]

Parameter	n	min	max	Geometric mean
Oral SF	175	0.00095	150000	**0.707**
Inhalation SF	105	0.00165	150000	**1.70**
Oral NOAEL	160	9E-08	3494	**14.0**
Inhalation NOAEL	84	0.006	245000	**68.7**
Fish LC50	221	0.001	227634	**24.6**
Fish NOEL	199	0.001	56909	**3.90**

[a] The chemical data used to generate the geometric means are listed in Tables E-X through E-X.

APPENDIX F:
SUMMARY OF INDUSTRY PERFORMANCE TESTING OF SOLDER

- Bhatia, G, and J. Siegel. “Summary of Lead-Free Solder Performance Based on Existing Data Provided by the Electronics Industry.” Report prepared for EPA Design for the Environment Program by Abt Associates, December, 2002.

Appendix F

F.1 INTRODUCTION

F.1.1 SCOPE

This appendix summarizes existing data on the performance of lead-free solders available in the electronics industry. In particular, it considers literature that referenced three specific alternative solder types: tin-copper (Sn-Cu), tin-silver-copper (Sn-Ag-Cu), and tin-silver-copper-bismuth (Sn-Ag-Cu-Bi). Additionally, it includes performance data for the tin-lead (Sn-Pb) alloy, as several literature sources compare alternative alloy data with existing tin-lead standards. This document is intended to provide EPA's Design for the Environment (DfE) *Lead-free Solder Partnership* and other interested parties with a consolidated source of key lead-free solder performance data. It identifies and summarizes existing data as well as documents these sources for further research.

During a preliminary literature search, lead-free solder performance data available in the electronics industry were found to be varied; alloy compositions as well as performance tests carried out on the alternative solders differed. As this appendix intends to be inclusive rather than overlook key applicable results, it includes summaries of documents that reference alloy compositions falling within the alloy families considered (for example, Sn-3Ag-4Cu and Sn-0.5Ag-4Cu fall under the ternary Sn-Ag-Cu alloy family). However, it should be noted that multiple sources have illustrated that performance results vary when an alloy's composition was altered. For example, Lau et al. cite that the elongation of the tin-silver-copper system drops rapidly with increasing bismuth content until it reaches the 3% level, where the elongation decreases slowly and later levels off with a further increase in Bi content. As a result, performance data for alloys were not limited to the compositions as defined by the EPA's DfE *Lead-free Solder Partnership* (see Table F.1.1.1), but included relevant data for alloy compositions close to the Partnership's selection.

Table F.1.1.1: EPA's DfE Lead-free Solder Partnership's Selection: Alloy Compositions and Family

DfE Lead-free Solder Partnership Selection, Alloy Composition	Alloy Family Considered
99.2% Tin and 0.8% Copper	Sn-Cu
95.5% Tin, 3.9% Silver, and 0.6% Copper	Sn-Ag-Cu
96.0% Tin, 2.5% Silver, 0.5% Copper, and 1.0% Bismuth	Sn-Ag-Cu-Bi

F.1.2 BACKGROUND

The Japanese Ministry of International Trade and Industry (MITI) proposed take-back legislation in Japan, requiring consumer and business users to return end-of-life (EOL) equipment to retailers for recycling, making the manufacturer responsible for the cost of recycling. In response to this and other proposed legislation, several major Japanese electronics manufacturers initiated their own roadmaps and publicly announced accelerated plans to eliminate lead-solder from certain or all products. Companies making this commitment included Matsushita, Sony, Toshiba, and Hitachi, with others likely to follow. Currently, Matsushita is successfully marketing lead-free consumer products; Sony has a goal of eliminating lead from products, except for a few uses, by the end of March 2005; and Toshiba's general policy is that all products are available lead-free by the end of 2003. Supplementary to this, published on 13 February, 2003, the European Directive on Waste Electrical and Electronic Equipment (WEEE) requires the substitution of lead, amongst other listed heavy metals, in new electrical and electronic equipment. The Directive is to become effective on 13 August, 2005[1]. These changes in international legislation will potentially eliminate lead from electronic devices produced in the European Union and by foreign competition, thus, driving the implementation of lead-free assembly around the world.

As a result of international legislative and market pressures to phase-out the use of tin-lead solders, the use of lead-free solder alternatives in electronic products manufactured in the U.S. has also received increasing attention. This worldwide shift to lead-free products gives rise to several questions, key among them is the performance of alternative solders. In search of a substitute alloy(s), researchers have conducted numerous performance tests on a host of alternative alloys.

A large number of the alternative solders being considered as a replacement for Sn-Pb are rich in tin and coupled with additional elements to enhance alloy characteristics. Solder performance is determined by testing the alternative solder for characteristics such as joint strength, fatigue resistance[2], and high temperature life. Preliminary literature searches provided some basic information on the elements considered for lead-free solder alloys. For example, silver is comparatively available in abundance, however, it is high in cost. Bismuth poses potential problems with supply as well as embrittlement (as lead contamination drops its melting temperature causing joint embrittlement). Copper on the other hand, is readily available as well as soluble in tin. Additionally, copper-containing tin alloys have been used by the industry in the past.

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[1] U.K. Department of Trade and Industry, 2005, Sustainable Development and Environment; accessed at: http://www.dti.gov.uk/sustainability/weee/

[2] Fatigue resistance: The maximum stress that a material can endure for a given time without breaking.

F.2 LITERATURE SUMMARY

Research of alternative solders' performance was found to be taking place on a large scale by multi-stakeholder partnerships and industry sectors, academia, and non-regulatory federal agencies (for example, the National Institute of Science and Technology). It was also found that a large number of studies were ongoing with performance data that is yet to be released. For example, the High Density Packaging (HDP) User Group International studies regarding solder reliability characterization was an ongoing research project during the time this appendix was written; results were later released in 2003[3].

The studies that were reviewed for this appendix were found difficult to compare; studies differed in their focus and often considered different alloy combinations and performance tests. Additionally, resulting data were presented in varying metrics. Such disparities in the available data hindered the comparability of performance results across sources.

In order to present these data in the most useful format, a summary of each paper is provided in this section (Section F.2). Select quantitative data from the individual studies have been presented in Section F.3. Qualitative data have been summarized in Section F.4.

It should be noted that these literature sources often referenced more alloys than those summarized. In order to remain within the scope of this document, only those alloys of interest to the Partnership have been presented.

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[3] Results became available after the research for this appendix concluded. Results were presented in four papers at the APEX 2003 Conference. The papers presented were: Lead-Free Design, Materials, and Process of High Density Packages, Joe Smetana, Alcatel; Lead-Free Solder Joint Reliability of High Density Packages - Part I: Design For Reliability, Walter Dauksher, Ph.D., Agilent; Lead-Free Solder Joint Reliability of High Density Packages-Part II: Reliability Testing and Data Analysis, John Lau, Ph.D., Agilent Technologies; and Lead-Free Solder Joint Reliability of High Density Packages - Part III: Failure Analysis, Dongkai Shangguan, Ph.D., Flextronics International.

Table F.2.1: List of the Summarized Literature, Solders Addressed, and the Focus of Each Study

Section No.	Title	Authors	Organization	Solders Addressed			Study Focus
				Sn-Cu	Sn-Ag-Cu	Sn-Ag-Cu-Bi	
1.	Electronics Manufacturing with Lead-Free, Halogen Free & Conductive-Adhesive Materials	John H. Lau, C.P. Wong, Ning-Cheng Lee, S.W. Ricky Lee	Agilent Technologies, Inc., Georgia Institute of Technology, Nin-Cheng Lee, Hong Kong University of Science and Technology, respectively	✓	✓	✓	- Physical properties - Mechanical properties - Wetting properties - Reliability properties
2.	Reliability of Solder Joints Assembled with Lead-Free Solder	Masayuki Ochiai, Toshiya Akamatsu, Hidefumi Ueda	Fujitsu Laboratories Ltd., Japan		✓		- Mechanical properties at twisting - Fatigue life subjected to twisting - Solder ball joints of BGA packages - Solder joints of QFPs
3.	The Solder Programme	William J. Plumridge	The Open University Materials Engineering Department, UK	✓	✓		- Tensile properties - Fatigue response - Creep behavior
4.	Mechanical Properties of Sn-3.0mass%Ag-0.5mass%Cu Alloy	Yoshiharu Kariya, William Plumbridge	The Open University Materials Engineering Department, UK		✓		- Tensile behavior - Creep behavior
5.	Properties of Lead Free Alloy and Performance Properties of Lead Free No-Clean Solder Paste	Quan Sheng, Sandy Kwiatek	OMG Americas		✓		- Mechanical properties - Creep performance - Wetting properties (No-clean solder paste system)
6.	Lead-FREE Alloys: Fitting the Square Peg in the Square Hole	Angela Grusd, Chris Jorgensen	Heraeus Cermalloy, IPC - Association Connecting Electronics Industries, respectively	✓	✓		- Physical properties - Creep/Fatigue - Wettability
7.	Research Update: Lead-Free Solder Alternatives	Jasbir Bath, Carol Handwerker, Edwin Bradley	National Electronics Manufacturing Initiative (NEMI)	✓	✓		- Physical properties - Reliability - Reflow and wave soldering - Mechanical properties
8.	AIM: Technical Data Sheet	AIM	AIM	✓	✓		- Mechanical properties - Wetting properties - Fatigue resistance - Solder joint reliability - Wave Soldering and SMT applications
9.	Materials and Process Considerations for Lead-Free Electronics Assembly	Karl Seelig and David Suraski	AIM	✓	✓		- Physical properties - Mechanical properties - Wetting properties - Reliability testing
10.	Database for Solder Properties with Emphasis on New Lead-free Solders	NIST and CSM	National Institute of Standards & Technology (NIST) and Colorado School of Mines (CSM)	✓	✓	✓	- Physical properties - Mechanical properties - Thermal properties

F.2.1 Electronics Manufacturing With Lead-Free, Halogen Free & Conductive-Adhesive Materials

Author(s):	John H. Lau, C.P. Wong, Ning-Cheng Lee, S.W. Ricky Lee
Organization:	by author: Agilent Technologies, Inc., Georgia Institute of Technology, Nin-Cheng Lee, Hong Kong University of Science and Technology, respectively
Publication/Source:	McGraw-Hill, Ch. 13: Prevailing Lead-Free Alloys, p. 13.1-13.62
Date:	September 2000
DfE Alloys Considered:	Sn-Cu, Sn-Ag-Cu, Sn-Ag-Cu-Bi

Summary: This is a comprehensive handbook, covering integrated circuit (IC) packaging, printed circuit board (PCB)/substrates, assembly of IC packages, and novel conductive adhesive materials. Emphasis is on fundamental principles, engineering data, and manufacturing technologies. Among others, this source considers the Sn-Cu, Sn-Ag-Cu and Sn-Ag-Cu-Bi alloys.

Physical properties*:* Eutectic[4] Sn-Cu has the highest melting temperature among prevailing lead-free solders, suggesting greater difficulty in adopting this alloy. The ternary eutectic composition (approximately 95.6Sn-3.5Ag-0.9Cu) has a melting point of 217°C, while the melting temperature for Sn-Ag-Cu-Bi ranges between 207-216°C. Sn-Cu is comparable in surface tension, electrical resistivity, and density with Sn-Ag, Sn-Ag-Cu and Sn-Ag-Cu-*X* due to the dominant presence of tin. The hardness however, does vary; that of the ternary alloy is comparable with Sn-Pb. Bismuth-containing alloys on the other hand exhibit considerably higher hardness than Sn-Pb due to the precipitation and Bi-dissolution strengthening mechanisms. (For specific results, see Section F.3, Table F.3.1.a)

Mechanical properties: Eutectic Sn-Cu is lower in tensile strength but higher in elongation than both eutectic Sn-Ag and Sn-Pb, reflecting its softness and ductility. The tensile strength of Sn-Ag-Cu is higher than eutectic Sn-Pb. Near the ternary eutectic point, Sn-Ag-Cu alloys are higher than Sn-Pb in yield strength, shear strength, impact strength, and creep[5] resistance. For Sn-Ag-Cu alloys further away from ternary eutectic composition, the melting temperature (214 to 244°C) increases, as well as the tensile and shear strengths, at the expense of reduction in elongation. Sn-Ag-Cu-Bi alloys exhibit a higher tensile strength and yield strength, a lower elongation and a slower creep rate as compared to eutectic Sn-Pb. Shear strength of Sn-Cu is comparable with Sn-Pb. The creep strength of Sn-Cu is higher than 100Sn, but lower than Sn-Ag-Cu at both 20 and 100°C. At 25 and 100°C, the time to rupture increases in the following order: eutectic Sn-Ag, Sn-Ag-Cu < eutectic Sn-Cu < 60Sn-40Pb. The ternary Sn-3.5Ag-0.75Cu

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[4] Eutectic: having the lowest melting point possible. For Sn-Cu this is implies 99.3% Tin and 0.7% Copper.

[5] Creep: under constant load or stress, solder undergoes progressive inelastic deformations over time. This time dependent deformation is called creep.

alloy exhibits the longest time to break in creep tests. The tensile strength and creep resistance of this system increases with an increase in Bi content, then levels off at approximately 7-10% Bi. Elongation of this system, however, drops rapidly with increasing Bi content until it reaches the 3% level, then it decreases slowly and later levels off with additional Bi content. (For specific results, see Section F.3, Tables F.3.1.b and F.3.1.c)

Wetting properties: The wetting properties of eutectic Sn-Cu show great potential as replacements for Sn-Pb in wave and reflow processes. Tests show that the wetting ability of alloys decreases in the following order: eutectic Sn-Pb > Sn-Ag-Cu > Sn-Ag > Sn-Cu when an unactivated flux is used. The difference in wetting diminishes when an activated flux is used and when the wetting time is plotted against superheating. At 260°C, the wetting time descends in the following order: 96Sn-2.5Ag-1Bi-0.5Cu > 96.2Sn-2.5Ag-0.5Sb-0.8Cu > 63Sn-37Pb > 99.3Sn-0.7Cu > 96.5Sn-3.5Ag > 95.5Sn-4Ag-0.5Cu. Wetting time studies conducted by the meniscograph method presented increasing wetting times for solders in the following order: 63Sn-37Pb < Sn-Ag-Cu-2Bi ~ Sn-Ag-Cu-1Bi < Sn-3.5Ag-0.75Cu < Sn-1Ag-0.5Cu < Sn-0.7Cu-0.3Ag < Sn-0.75Cu. However, the wetting time decreases with increasing temperature at a slightly different rate. Finally, both Sn-Ag-Cu-1Bi and Sn-Ag-Cu-2Bi were found to display wetting behavior that is fairly comparable with 63Sn-37Pb.

The reflow spreading of eutectic Sn-Cu is better than eutectic Sn-Ag, but poorer than eutectic Sn-Pb. Studies presented the following spreading behavior in decreasing order: 63Sn-37Pb > Sn-Ag-Cu-4.5Bi, Sn-Ag-Cu-7.5Bi > Sn-3.5Ag-0.75Cu > 99.25Sn-0.75Cu. This source states that preferably the use of eutectic Sn-Cu should be confined to wave soldering. Varying references ranged wetting times for the Sn-Ag-Cu alloy from 0.23 to 1.1 seconds, while spreading behavior ranged between 3.9 to 5 and contact angle ranged between 21 to 47 degrees. The presence of Bi significantly improves the solder spreading properties of lead-free solders. The Sn-Ag-Cu-Bi system is outstanding in creep resistance and wetting. (For specific results, see Section F.3, Table F.3.1.d)

Reliability: The tensile strength of the eutectic Sn-Cu is fairly poor, however its fatigue resistance is fairly good. One study showed fatigue resistance to increase in the following order: 63Sn-97Pb < 64Sn-36In < 58Bi-42Sn < 50Sn-50In < 99.25Sn-0.75Cu < 100Sn < 96Sn-4Cu. However, the low-cycle isothermal fatigue (strain 0.2%, 0.1 Hz, R=0.8, 300 K) performance shows that the number of cycles to failure for eutectic Sn-Cu is less than one-third of that for eutectic Sn-Pb, while ternary 95.4Sn-3.1Ag-1.5Cu is significantly greater. For the two cases in this study which compared Sn-Cu with Sn-Pb, Sn-Cu is consistently better. For a 12-mm, 144-flexible ball grid array (fleXBGA) assembly at different cycling temperatures, Sn-Ag was the best, with low or no failure rates. The ternary Sn-4Ag-0.5Cu and Sn-3.4Ag-0.7Cu are similar to each other and also have better performance than eutectic Sn-Pb. At -40 to 125°C cycling, however, Sn-Cu performs similarly to Sn-Pb and little improvement is shown for Sn-Ag-Cu over Sn-Pb. In this range, eutectic Sn-Ag is again the best performer. For temperature cycling performance in ball grid array (BGA) assembly, eutectic Sn-Ag appears to be superior to Sn-Cu, but the opposite is observed for flip-chip assembly. It was reported that the thermal fatigue[6] life for flip-chip assembly descends in the following order: eutectic Sn-Cu > Sn-3.8Ag-0.7Cu, eutectic Sn-Pb > eutectic Sn-Ag.

The presence of Bi in the lead-free alloys can form a 52Bi-30Pb-18Sn ternary eutectic structure in the solidified solder joint which has a melting temperature of 96°C. This can be a concern because the solder joints become weak when subjected to thermal cycling. Lau et al., present additional data on temperature cycling and heat treatment reliability for Sn-Ag-Cu as well as Sn-Ag-Cu-Bi. In all the reported results, the Sn-Ag-Cu system is the prevailing alternative to lead-containing solder. (For specific results, see Section F.3, Tables F.3.1.a to F.3.1.d)

F.2.2 Reliability of Solder Joints Assembled with Lead-Free Solder

Author(s):	Masayuki Ochiai, Toshiya Akamatsu, Hidefumi Ueda
Organization:	Fujitsu Laboratories Ltd., Atsugi, Japan
Publication/Source:	Fujitsu Science Technology Journal, **38**, 1, p. 96-101
Date:	June 2002
DfE Alloys Considered:	Sn-Pb, Sn-Ag-Cu

Summary: The dynamic mechanical properties and reliability of Sn-Ag-Cu were tested in this study. Compared to the eutectic Sn-Pb solder, the ternary alloy was found harder to deform and more resistant to hardening, thus having a longer fatigue life.

Dynamic mechanical properties at twisting, temperature dependence: The shear modulus (similar to Young's modulus for tension, but indicates the ratio of a shear stress to its resulting shear strain) of both Sn-Pb and Sn-Ag-Cu decreased with rising temperature. The tin-lead alloy, however, had a much larger rate of decrease than the ternary alloy, showing that the former softens faster than the latter with increasing temperatures. It was also found that the Sn-Ag-Cu solder is more difficult to deform and less likely to harden than the Sn-Pb solder; therefore, it has a longer fatigue life.

Influence of twisting velocity on dynamic mechanical properties: The tin-lead solder was found to deform easily at twisting velocities below 1 rad/s (i.e., the range of twisting velocities that solder joints are subjected to in normal equipment operation). The ternary alloy was shown to be difficult to deform plastically and thus less likely to harden.

Fatigue life of solders subjected to twisting cycles: The fatigue life of Sn-Ag-Cu solder was approximately 10,000 cycles, almost twice the fatigue life of the Sn-Pb solder. These results again indicate that compared to the tin-lead solder, Sn-Ag-Cu is harder to deform plastically and therefore less likely to harden. This suggests that the ternary alloy has sufficient fatigue

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[6] Thermal fatigue: premature failure resulting from cycling stresses due to temperature changes.

resistance for use in electronics assembly.

Solder ball joints of BGA (Ball Grid Array) packages during transition to lead-free soldering: While in transition, lead and lead-free solders will be used combined in BGA ball joints. Mixing Sn-Ag-Cu solder with Sn-Pb was found to reduce the fatigue life slightly, maintaining its superiority to that of the Sn-Pb solder. This suggests sufficient reliability for the mixed solder joint.

Solder joints of QFPs (Quad Flat Pack) after transition to lead-free soldering: After the transition, QFP leads will be plated with lead-free solder, contaminating the joints with lead-free solder plating. A plating composition of Sn-2Bi presented an approximate 30% reduction in fatigue life in the Sn-Ag-Cu solder. However, the fatigue life was still superior to that of the Sn-Pb solder. It was concluded that Sn-Ag-Cu solder joints, with an expected level of bismuth contamination, will have a fatigue life comparable to current Sn-Pb solder joints. (For specific results, see Section F.3, Table F.3.2)

F.2.3 The Solder Programme at the Open University Materials Engineering Department: An Update, 2001

Author(s):	William J. Plumbridge
Organization:	Materials Engineering Department, The Open University, Buckinghamshire, U.K.
Publication/Source:	Materials Engineering Department, The Open University, UK. (http://technology.open.ac.uk/materials/mat-hp.html)
Date:	2001
DfE Alloys Considered:	Sn-Pb, Sn-Cu, Sn-Ag-Cu

Summary: The Open University program has been directed towards the testing performance of solder joints. This source briefly reviews the background and current status of the research into solder alloys and solder interconnections for use in electronics. It presents in-depth results for fatigue, creep and fatigue-creep interactions at high temperatures. It considers the Sn-0.5Cu and ternary Sn-3.8Ag-0.7Cu alloys.

Tensile Properties: The behavior of the referenced alloys was tested at temperatures between -10 and 75°C and strain rates between 10^{-1} and $10^{-6}s^{-1}$. Temperature and strain rate were found to have a substantial effect on strength. Raising the temperature from -10 to 75°C was found to reduce the tensile strength by approximately 75% of its value at -10°C (for example, the Sn-Pb and Sn-Cu alloys fell below 10 MPa at 75°C with a strain rate of $10^{-6}s^{-1}$). Ductility trends with temperature and strain rate were seen to be small and inconsistent. The Sn-Ag-Cu and Sn-Ag alloys display the smallest elongation to failure although the ductility values of all the alloys fall between 20 and 55%. The Sn-0.5Cu solder is usually the weakest and most ductile of the tested alloys, whereas comparatively, the Sn-Ag-Cu alloy is the strongest (with strength being greatest at -10°C with the fastest straining rates). This paper finds that the “inter-relationships between strength, ductility, temperature and strain rate are complex, and the relative merits of the alloys may change according to the test conditions."

Fatigue Response: Fatigue tests were carried out at room temperature and at 75^{o}C on Sn-37Pb, Sn-0.5Cu, and Sn-3.5Ag, exhibiting softening (around 15-20%) when subjected to strain controlled cycling. The incorporation of a dwell in the strain cycle reduces the number of cycles to failure in comparison with continuous cycling, irrespective of the dwell location. Generally, longer dwells result in lower numbers of cycles to failure, with balanced dwells resulting in the shortest life times.

Creep Behavior: Creep testing was carried out between -50^{o}C and 130^{o}C and times to rupture were examined up to several thousand hours. The creep behavior of the Sn-0.5Cu alloy is similar to that of Sn-37Pb at 75^{o}C, while Sn-Ag-Cu exhibits much greater creep resistance that appears to increase at lower stress levels. Both the silver-containing alloys exhibit a much greater creep resistance than Sn-37Pb, appearing to increase at lower stress levels. This superior creep performance is intrinsic to the alloy, as greater life is retained when testing at the same homologous temperatures to non-silver alloys. At high temperatures (for example, 99^{o}C), the rupture time of the silver-containing alloys are extremely sensitive to stress, where minor changes in service conditions could result in profound consequences on creep life. Lead-free alloys show lower creep ductility as compared with the eutectic Sn-37Pb (approximately 40%) at 75^{o}C. The creep ductility of the silver-containing alloys is the lowest at around 20%, and appears to be unaffected by applied stress.

Tin Pest: Tin pest can be found in the Sn-0.5Cu alloy when stored for over a year at temperatures below 13^{o}C. Here white tin transforms to grey tin with a substantial increase in volume, resulting primarily in surface wart formation and cracking, and finally in complete disintegration. (For specific results, see Section F.3, Table F.3.3)

F.2.4 Mechanical Properties of Sn-3.0mass%Ag-0.5%mass%Cu Alloy

Author(s):	Yoshiharu Kariya and William J. Plumbridge
Organization:	Materials Engineering Department, The Open University, Buckinghamshire, U.K.
Publication/Source:	Materials Engineering Department, The Open University, U.K.
Date:	Not Provided
DfE Alloys Considered:	Sn-Ag-Cu

Summary:	This paper investigates the tensile and creep behavior of Sn-3.0Ag-0.5Cu in the rapidly cooled, as-cast state, and compares it with Sn-3.8Ag-0.7Cu and Sn-3.5Ag. Temperature for the tensile tests ranged between 263K and 398K, and the constant load creep tests were performed at 348K.

The ternary alloys, Sn-3.0Ag-0.5Cu and Sn-3.8Ag-0.7Cu, were found to have similar tensile strengths, where tensile strength was found to decrease with increasing temperature and with decreasing strain rate. The tensile strength for the former alloy was 20% higher than Sn-3.5Ag and double that observed in Sn-0.5Cu at a strain rate of 10^{-3}/s and 348K. Both Sn-3.0Ag-0.5Cu and Sn-3.8Ag-0.7Cu were shown to be superior to the Sn-3.5Ag alloy in this characteristic.

The creep resistance of both the ternary alloys were found to be comparable to each other and clearly superior to the Sn-Ag alloy. Applied stress had little effect on the creep ductility of the alloys, with the creep ductility of Sn-3.0Ag-0.5Cu being almost equivalent to eutectic Sn-Ag and the standard Sn-Ag-Cu for this property. (For specific results, see Section F.3, Table F.3.4)

F.2.5 Properties of Lead Free Alloy and Performance Properties of Lead Free No-Clean Solder Paste

Author(s): Quan Sheng, Charles Bradshaw, Sandy Kwiatek
Organization: OMG Americas, Research Triangle Park, NC
Publication/Source: Presented at IPC SMEMA Council APEX® 2002 (www.goapex.org)
Date: 2002
DfE Alloys Considered: Sn-Pb, Sn-Ag-Cu

Summary: This paper examines the development of a no-clean solder paste system with the unique needs of the 214-220ºC melting point of lead-free alloys. The properties of the Sn-3.5Ag-0.5Cu no-clean solder paste are compared to 63Sn-37Pb no-clean solder paste.

Mechanical properties of the two alloys compared favorably, showing slightly lower ultimate tensile strength and yield strength for the lead-free alloy. Elongation results were inconsistent for the two alloys. Creep performance of the ternary alloy in bulk was found to be superior to the 63Sn-Pb alloy. Wetting properties of solder joints made with both pastes were found to be comparable. Both alloys demonstrated similar static viscosity, dynamic viscosity, tack, printability, solderability, wide reflow window, and reflow characteristics. Finally, the lead-free no-clean paste was found to potentially have a longer print life than 63Sn-Pb. From a performance standpoint, lead-free no-clean Sn-3.5Ag-0.5Cu paste has similar characteristics to 63Sn-Pb, and could be used for PCB applications. (For specific results, see Section F.3, Table F.3.5)

F.2.6 Lead-FREE Alloys: Fitting the Square Peg in the Square Hole

Author(s): Angela Grusd and Chris Jorgensen
Organization: Heraeus Cermalloy and IPC - Association Connecting Electronics Industries
Publication/Source: Circuitree, p. 98-102
DfE Alloys Considered: September 1999
DfE Alloys Considered: Sn-Cu, Sn-Ag-Cu

Summary: This paper provides an overview of numerous lead-free alloys, examining temperature ratings, cost, and other factors. It notes that two alloys–99.3Sn-0.7Cu and 95.5Sn-4.0Ag-0.5Cu–have mid-range melting temperatures (i.e. between 200^{o}C-230^{o}C), slightly higher than that of tin-lead, and have been popular choices in the industry, particularly in the case of reflow soldering.

Tin-Copper: The melting temperature for this alloy (99.3Sn-0.7Cu) is 227^{o}C. This alloy may prove suitable for high-temperature applications such as those required by the automotive industry. Testing shows significant improvement in creep/fatigue data over Sn-Pb alloy. However, the Sn-Ag-*X* alloys are found to perform better in creep testing.

Tin-Silver-Copper: The melting temperature for this alloy (95.5Sn-4.0Ag-0.5Cu) falls between 217-219^{o}C. This temperature range makes it well-suited for high operation temperatures (up to 175^{o}C). The mechanical stability of the joint is degraded when the melting point of the solder is approached. Thus, elevated temperature cycling produces less damage with higher melting point solders than it does for Sn-Pb solders (melting point of 183^{o}C). These solders however, do not wet copper as well as the eutectic Sn-Pb solder using commercial fluxes. However, if the fluxes are suited for high-temperature use, good fillet formation can be achieved. Wettability can also be improved using no-clean fluxes when soldering in nitrogen atmosphere. This paper points out that there are other factors besides performance, such as cost, to consider when selecting a lead-free alloy. (For specific results, see Section F.3, Table F.3.6)

F.2.7 Research Update: Lead-Free Solder Alternatives

Author(s): Jasbir Bath, Carol Handwerker, Edwin Bradley
Organization: National Electronics Manufacturing Initiative (NEMI)
Publication/Source: Circuits Assembly (www.circuitassembly.com), p. 31-40.
Date: May 2000
DfE Alloys Considered: Sn-Cu, Sn-Ag-Cu

Summary: This paper identifies Sn-3.9Ag-0.6Cu as the recommended choice for reflow soldering, and Sn-0.7Cu or Sn-3.5Ag as the recommended choices for wave soldering. It provides an update on current research for lead-free solder alternatives, and makes note that further investigations are being conducted on the alternative alloys.

Tin-Copper: The eutectic alloy Sn-0.7Cu has a melting temperature of 227°C. Reliability data indicates it is similar to Sn-37Pb for surface-mount use. Due to a melting temperature 10°C higher than the ternary Sn-Ag-Cu alloy, Sn-0.7Cu is found undesirable for reflow applications. This temperature does not present the same concern for wave soldering applications. This paper makes note of a tendency for fillet lifting when using tin-silver, tin-copper or tin-silver-copper alloys for wave soldering with lead containing surface finishes, due to the presence of lead. A significant advantage to using Sn-0.7Cu is the low cost of bar solder.

Tin-Silver-Copper: Alloys within this family with a melting range between 217°C and 222°C are good substitutes for tin-lead solder. The European IDEALS consortium recommended the Sn-3.8Ag-0.7Cu alloy as the best lead-free alloy for reflow. Reliability for this alloy composition was found equivalent to or better than the Sn-Pb and Sn-Pb-Ag alloys.

Within this ternary alloy family, several readily available alloys–Sn-3.5Ag-0.7Cu, Sn-3.6Ag-0.9Cu, Sn-3.8Ag-0.7Cu, as well as Sn-4Ag-0.5Cu--have melting temperatures near 217°C. Alloy compositions within the range of Sn-3.5 to 4% (weight) Ag-0.5 to 1% (weight) Cu are close enough to the eutectic to have similar liquidus[7] temperatures, microstructures and mechanical properties. Bath et al. note that results from literature and solder vendors indicate that the solderability of the ternary alloy is adequate, however, like all lead-free alloys, worse than eutectic Sn-Pb.

The NEMI Lead-Free Task Force decided on the Sn-3.9Ag-0.6Cu solder as their recommendation to the industry for reflow soldering. For wave soldering the recommended choices are Sn-0.7Cu and Sn-3.5Ag. The NEMI Lead-Free Task Force is continuing to investigate the performance of these substitutes. Updated information can be found on the NEMI web page: http://www.nemi.org/newsroom/Presentations/index.html. (For specific results, see Section F.3, Table F.3.7)

F.2.8 AIM: Technical Data Sheet

Organization:	AIM (a global manufacturer of electronics soldering materials)
Publication/Source:	AIM: Technical Articles: Lead-free Product Data Sheets (http://www.aimsolder.com/leadfree_tdss.cfm?section=assembly)
Dated:	Not Provided
DfE Alloys Considered:	Sn-Cu, Sn-Ag-Cu

Summary: AIM's Technical Data Sheets present the characteristics of select lead-free solder alloys. The alloys relevant to the scope of this study are: Sn-0.7Cu, Sn-3Ag-0.5Cu (LF218™), and Sn-3.8-4.0Ag-0.5-0.7Cu (TSC-4).

Tin-Copper: The Sn-0.7Cu alloy is high in purity with a high melting temperature of 227°C.

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[7] Liquidus: the lowest temperature at which a metal or alloy is completely liquid.

This eutectic alloy can be used for high temperature lead-free applications.

Tin-Silver-Copper: The Sn-3.8-4.0Ag-0.5-0.7Cu alloy has a low melting point of 217-218°C, good wetting properties, excellent fatigue resistance, excellent solder joint reliability and is compatible with all flux types. The Sn-3Ag-0.5Cu (LF218$^{\text{TM}}$) alloy also has a melting point of 217-218°C and falls under the JEIDA recommendation for lead-free soldering. These two ternary alloys are near drop-in replacements for eutectic Sn-37Pb in both wave and hand soldering applications. In wave soldering, both these alloys produce less dross than other solder alloys, wet well, and provide superior joint strength. In SMT (Surface-Mount Technology) applications, they produce stronger solder joints, have greater mechanical fatigue resistance, and are good substitutes for the eutectic tin-lead alloy. Additionally, the Sn-3Ag-0.5Cu and Sn-3.8-4.0Ag-0.5-0.7Cu no-clean solder pastes pass all Bellcore and IPC specifications. (For specific results, see Section F.3, Table F.3.8)

F.2.9 Materials and Process Considerations for Lead-Free Electronics Assembly

Author(s): Karl Seelig[8] and David Suraski
Organization: AIM
Publication/Source: AIM: Lead-free Articles (http://www.aimsolder.com/lead_free.cfm?section=articles#2)
Date: Not provided
DfE Alloys Considered: Sn-Cu, Sn-Ag-Cu

Summary: This paper presents analyses of tin-silver, tin-copper, and tin-silver-copper alloys and compares reliability testing results and process considerations for them. In order to obtain reliability results, the alloys were subjected to various thermal and mechanical fatigue tests. The paper also briefly discusses cost and patent issues related to these solders.

Tin-Copper: While tin-copper solders may be less costly than those containing silver, there are other issues to consider. The Sn-0.7Cu alloy has a melting temperature of 227°C, prohibiting its use for many temperature-sensitive applications. It is also a poor wetting alloy compared to other lead-free solders. This could require the use of nitrogen and aggressive fluxes for many applications and may result in wetting-related defects. Additionally, Sn-Cu typically has lower capillary action to draw it into barrels during Plated Through Hole (PTH) Technology and lacks the fatigue resistance needed for surface mount assembly. Finally, the poor fatigue characteristics of this alloy may result in field failures, which negates initial cost savings provided by this less-expensive alloy.

Tin-Silver-Copper: Most of the world seems to be looking to the Sn-Ag-Cu family of alloys as a

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[8] Note: Karl Seelig, AIM, has provided a number of technical papers presenting results of lead-free solder alloys, often presenting overlapping data. It should also be noted that Table F.3.9 combines performance data from several of these sources (including literature not summarized in this appendix, but listed under *References*).

substitute for lead solder alloys. The Sn-4Ag-0.5Cu alloy has a melting point of 218°C and its base materials are abundantly available. It offers very good fatigue characteristics and good overall joint strength. Wetting tests demonstrate that alloys with lower silver contents (for example, Sn-2.5Ag-0.7Cu-0.5Sb) wet stronger and faster than those with higher silver contents (for example, Sn-4Ag-0.5Cu). However, the silver content of this alloy makes it cost prohibitive for some applications. Further, silver-containing alloys have experienced failure during fatigue testing, due to a phase change which causes structural weakness. The low silver alloys can reduce this problem and offer improved wetting and slightly lower melting temperatures. The low silver alloys are available worldwide, provide the advantages of the Sn-Ag-Cu family of alloys, are less cost prohibitive, and avoid the problems associated with Sn-Cu and dual-alloy processes.

Dual Alloy Assembly: Apart from problems associated with Sn-Cu, intermixing Sn-Ag-Cu and Sn-Cu solders may result in non-uniformly alloyed solder joints. This may cause the joint to be susceptible to fatigue failure due to inability to relieve stress and strain. Further, when repairs or touch-ups are needed, two inventories of alloys are required and operators must be sure not to mix the alloys.

Reliability - Thermal Cycling Testing: Test boards were built using Sn-0.7Cu and Sn-4Ag-0.5Cu in conjunction with 1206 thin film resistors. The boards were thermally shocked from -40 to 125°C for 300, 400 and 500 15-minute cycles. Post-test inspections show that the Sn-Cu alloy exhibited some cracked solder joints as a result of poor wetting. In addition, well-formed solder joints made from the Sn-Cu alloy also showed cracks on the third set of boards cycled to 500 repetitions. The Sn-4Ag-0.5Cu alloy on the other hand, did not show any cracks during testing up to 500 repetitions, demonstrating that it has significantly superior thermal fatigue resistance as compared to Sn-Cu. However, it should be noted that the Sn-4Ag-0.5Cu alloy did exhibit some change in grain structure throughout the joint subsequent to the thermal cycling.

Mechanical Strength-Flex Testing: To test the solders' mechanical strength, test boards were built using the two alloys in conjunction with 1206 thin film resistors, and were subjected to flex testing. The test results show that solder joints produced from Sn-0.7Cu cracked during flex testing, indicating a weak joint that is unable to withstand a wide range of mechanical stresses. On the contrary, solder joints produced from Sn-4Ag-0.5Cu passed all flex test requirements. (For specific results, see Section F.3, Table F.3.9)

F.2.10 Database for Solder Properties with Emphasis on New Lead-free Solders Release 4.0

Organization:	National Institute of Standards & Technology (NIST) and Colorado School of Mines (CSM)
Publication/Source:	Properties of Lead-Free Solders (http://www.boulder.nist.gov/div853/lead%20free/props01.html)
Dated:	February 11, 2002 (last updated)
Alloys Considered:	Sn-Pb, Sn-Cu, Sn-Ag-Cu, Sn-Ag-Cu-Bi

Summary: This database summarizes the mechanical and thermal properties of lead-free alloys from numerous sources. These data were summarized in a series of tables. Excerpts of these tables have been presented in Section F.3, illustrating the properties of the tin-lead solder along with three lead-free solders in compositions identical or similar to those being examined by the DfE Partnership.

This source presents data on the shear strengths and wetting angles; mechanical properties such as ductility, tensile, physical; and thermal properties of multiple solder alloy compositions. (For specific results, see Section F.3, Tables F.3.10.a. through F.3.10.g)

F.3 PERFORMANCE TABLES

Table F.3.1.a: Physical Properties of Lead-free Solders, Summary Table

Alloy Family	**Sn-Pb**	**Sn-Cu**	**Sn-Ag-Cu**			**Sn-Ag-Cu-Bi**
Alloy Composition	63Sn-37Pb	99.3Sn-0.7Cu	95.5Sn-3.8Ag-0.7Cu	95.5Sn-4Ag-0.5Cu	95.4Sn-3.1Ag-1.5Cu	93.3Sn- 3.1Ag-3.1Bi-0.5Cu
Melting Temperature (°C)	183	227	217	217-255	216-217	209-212
Surface Tension (dyne/cm)	380 at 260°C, 417 at 233°C (air), 464 at 233°C (nitrogen)	491 at 277°C (air), 461 at 277°C (nitrogen)	–	–	–	–
Density (gm/cm^3)	8.36, 8.4	7.31	7.5	7.44, 7.39	–	7.56 (Sn-2Ag-0.5Cu-7.5Bi)
Thermal Conductivity (W/cm·°C)	0.509 at 30°C, 0.50 at 85°C	–	–	–	–	–
Electrical Resistivity (µO-cm)	14.5, 15.0, 17	10-15	13	10-15		10.6 (Sn-3Ag-3Cu-2Bi)
Hardness (Vickers hardness, kg/mm2 (HV); Brinell hardness (BH))	12.8 (HV), 17 (BH)	–	15 (BH)	–	–	34.5 (Sn-3Ag-3Cu-2Bi)
CTE (ppm)	18.74, 25, 21, 24	–	14.83 (Sn-3Ag-4Cu)	–	–	–

Source: Lau et al., "Electronics Manufacturing With Lead-Free, Halogen Free & Conductive-Adhesive Materials," September 2000.

– where alloys had no performance data.

CTE Coefficient of Thermal Expansion

Table F.3.1.b: Creep Behavior of Lead-free Solders, Summary Table

Alloy Family		Sn-Pb	Sn-Cu	Sn-Ag-Cu	Sn-Ag-Cu-Bi
Alloy Composition		63Sn-37Pb	99.3Sn-0.7Cu	95.5Sn-3.8Ag-0.7Cu	93.3Sn-3.1Ag-3.1Bi-0.5Cu
Creep Strength at 0.1 mm/min (N/mm^2)	20ºC	–	8.6	13	–
	100ºC	–	2.1	5	–
Creep at 25ºC (MPa)	100h to failure	6 (Sn-40Pb)	–	27 (Sn-4Ag-0.5Cu)	–
	1000h to failure	2.8 (Sn-40Pb)	–	7.5 (Sn-4Ag-0.5Cu)	–
Time to break (MPa)		–	–	323 (Sn-1Ag-0.5Cu); 3,849 (Sn-3.5Ag-0.75Cu)	218 (Sn-Ag-Cu-7.5Bi); 1747 (Sn-Ag-Cu-4.5Bi); 2203 (Sn-Ag-Cu-2Bi)
Number of Cycles to failure*		3,650	1,125	8,936 (95.4Sn-3.1Ag-1.5Cu)	6,522

Source: Lau et al., “Electronics Manufacturing With Lead-Free, Halogen Free & Conductive-Adhesive Materials,” September 2000.

[*] Relative performance in Fatigue Resistance of lead-free solders in low-cycle isothermal fatigue test (strain 0.2%; 0.1 Hz; R=0.8; 300K).

Table F.3.1.c: Mechanical Properties of Lead-free Solders, Summary Table

Alloy Family			Sn-Pb	Sn-Cu	Sn-Ag-Cu	Sn-Ag-Cu-Bi
Alloy Composition			63Sn-37Pb	99.3Sn-0.7Cu	95.5Sn-3.8Ag-0.7Cu	93.3Sn-3.1Ag-3.1Bi-0.5Cu
Ultimate Tensile Strength (MPa)			19-56[*]	23	48; 48.5 (95.4Sn-3.1Ag-1.5Cu)	78
Yield Strength (MPa)			27.2-37[**]	37	45	85.3 (Sn-2Ag-7.5Bi-0.5Cu)
Young’s Modulus (GPa)			38.1 (-70ºC), 30.2 (20ºC), 19.7 (140ºC), 32, 33.58, 35, 15.7, 31.03	–	–	–
Elongation (%)			31-58.87[***], 35-176[****]	45	36.5 (95.4Sn-3.1Ag-1.5Cu)	19
Shear Strength (MPa)	at 0.1 mm/min	20ºC	23	20-23	27	–
		100ºC	14	16-21	17	–
	at 0.1 mm/min; gap thickness: 76.2µm; cooling rate =10º/s	22ºC	36.5 (Sn-40Pb)	29.8	63.8	–
		170ºC	4.5 (Sn-40Pb)	10.1	25.1	–
	at 1 mm/min at reflow temperature (RT)		34.5 (Sn-40Pb)	28.5 (Sn-1Cu)	–	–
	at 1 mm/min at 100ºC		21.6 (Sn-40Pb)	21.2 (Sn-1Cu)	–	–
	By ring-and-plug test		40.27	–	–	–
Impact Strength (J/cm^2)			31	–	77 (Sn-3.5Ag-0.75Cu)	–

Source: Lau et al., “Electronics Manufacturing With Lead-Free, Halogen Free & Conductive-Adhesive Materials,” September 2000.

[*] The ultimate tensile strength values fall between 19 and 56 MPa (with an average of 39.47 MPa) as per ten references cited by Lau et al., Table 13.2.

[**] The yield strength values fall between 27.2 and 37 MPa (with an average of 30.62 MPa) as per four references cited by Lau et al., Table 13.2.

[***] The elongation values fall between 31 and 52.87% (mean 41.0%) as per six references cited by Lau et al., Table 13.2.

[****] The elongation value according to a reference cited by Lau et al., Table 13.2, ranged between 35-176 percent.

Table F.3.1.d: Wetting Properties of Lead-free Solders, Summary Table

Wetting Properties							
Alloy Family			**Sn-Pb**		**Sn-Ag-Cu**		**Sn-Ag-Cu-Bi**
Alloy Composition			60Sn-40Pb	62Sn-38Pb	95.5Sn-3.8Ag-0.7Cu	95.5Sn-4.7Ag-1.7Cu	Sn-3.3Ag-3Bi-1.1Cu
Contact Angle (degrees)	–		17	–	–	21	–
	Flux A611, 260-280ºC		22	–	–	47	–
	Flux A260HF, 260-280ºC		32	–	–	45	–
	Flux B2508, 260-280ºC		31	–	–	35	–
Wetting Time at 260ºC (seconds)	Immersion Pb PCB		–	0.36 (at 235ºC)	0.28	–	0.24
	Immersion Sn PCB		–	0.27 (at 235ºC)	0.23	–	0.26
	Immersion Ag PCB		–	0.20 (at 235ºC)	0.25	–	0.19
	NiAu, PCB		–	0.32 (at 235ºC)	0.42	–	0.44
	OSP 1		–	0.20 (at 235ºC)	0.26	–	0.26
	OSP 2		–	0.21 (at 235ºC)	0.23	–	0.25
	OSP 3		–	0.24 (at 235ºC)	0.27	–	0.27
Spread	OSP 3	A	–	4.55	4.2	–	4
		B	–	5	4.35	–	4.45
	Immersion Ag	A	–	4.7	4.55	–	4.6
		B	–	4.7	4.8	–	4.95
	Immersion Pd	A	–	4.4	3.9	–	4.4
		B	–	4.7	3.9	–	4.65
	NiAu	A	–	5	4.4	–	4.7
		B	–	5	5	–	5

Source: Lau et al., “Electronics Manufacturing With Lead-Free, Halogen Free & Conductive-Adhesive Materials,” September 2000.

Key:
A Peak 240ºC, dwell 60-s for Pb-free, 215ºC, 60-s dwell for Sn-Pb-Ag, scale 1 to 5 (best), forced-air convection, air.
B Peak 240ºC, dwell 60-s for Pb-free, 215ºC, 60-s dwell for Sn-Pb-Ag, scale 1 to 5 (best), 230ºC bp VPR.

Table F.3.2: Tin-Silver-Copper Solder Joint Reliability Compared with Sn-Pb, Summary Table

Alloy Family	**Temperature Dependence**				**QFP solder joints**
	Shear Modulus (at increasing temperature)	**Deformation** (twisting velocity below 1 rad/s)	**Hardening**	**Fatigue life**	**Fatigue life**
Sn-Pb	decreases (at a larger rate than Sn-Ag-Cu)	easily deformed	–	–	–
Sn-Ag-Cu	decreases (at a smaller rate than Sn-Pb)	more difficult to deform (than Sn-Pb)	less likely to harden (than Sn-Pb)	10,000 cycles (almost twice Sn-Pb)	superior (to Sn-Pb) with controlled Bi-contamination

Source: Ochiai et al., "Reliability of Solder Joints Assembled with Lead-Free Solder"

Table F.3.3: Tensile, Fatigue, and Creep Properties of Lead-free Alloys, Summary Table

Alloy Family	**Tensile Properties**			**Fatigue Tests***	**Creep Properties****	
	Elongation to Failure	**Ductility**	**Tensile Strength*****		**Creep Behavior (at 75°C)**	**Time to Rupture**
Sn-Pb	–	–	below 10MPa	softening (15-20%)	–	–
Sn-Cu	–	comparatively most ductile	below 10MPa (weakest)	softening (15-20%)	similar to Sn-37Pb	lower creep ductility than Sn-37Pb
Sn-Ag-Cu	comparatively smallest	20-55%	comparatively strongest	softening (15-20%)	greater creep resistance	extremely sensitive to stress

Source: William J. Plumbridge, The Solder Programme at the Open University Materials, Engineering Department: An Update, 2001 (http://technology.open.ac.uk/materials/mat-hp.html)

* At room temperature and at 75°C; subjected to strain controlled cycling.

** Between -50°C and 130°C; times to rupture examined up to several thousand hours.

*** At 75°C with a strain rate of $10^{-6}s^{-1}$.

Table F.3.4: Tensile and Creep Behavior of Two Sn-Ag-Cu Alloys in the Rapidly Cooled, As-Cast State, Summary Table

Alloy Composition	**Tensile Strength*** (Strain rate: 10^{-3}/s; 348K)	**Creep Resistance****	**Time to Rupture** (Stress component: approx. 14)
Sn-3Ag-0.5Cu	higher than Sn-3.5Ag (by 20%); double Sn-0.5Cu	better than Sn-3.5Ag	similar to Sn-3.8Ag-0.7Cu; superior than Sn-3.5Ag (x 20)
Sn-3.8Ag-0.7Cu	decreases (with increasing temperature & decreasing strain rate)	better than Sn-3.5Ag	–

Source: Yoshiharu Kariya and William J. Plumbridge, "Mechanical Properties of Sn-3.0mass%Ag-0.5%mass%Cu Alloy", Materials Engineering Department, The Open University, U.K.

* Tensile tests ranged between 263K and 398K.

** Constant load creep tests were carried out at 348K.

Table F.3.5: Tin-Silver-Copper Solder Performance Compared with Sn-Pb, Summary Table

Alloy Family	Sn-Pb	Sn-Ag-Cu
Solder Paste Alloy Composition	Sn-37Pb	Sn-3.5Ag-0.5Cu
Ultimate Tensile Strength	–	slighter lower than Sn-37Pb
Yield Strength	–	slighter lower than Sn-37Pb
Creep Performance	–	superior to Sn-37Pb
Wetting Properties	comparable	comparable
Viscosity (Static & Dynamic)	similar	similar
Tack	similar	similar
Solderability	similar	similar
Reflow Characteristics	similar	similar
Print life	–	longer than Sn-37Pb

Source: Quan Sheng, Charles Bradshaw, Sandy Kwiatek, “Properties of Lead Free Alloy and Performance Properties of Lead Free No-Clean Solder Paste”, OMG Americas, 2002

Table F.3.6: Creep Behavior and Wettability of Three Solder Alloys, Summary Table

Alloy Family	Alloy Composition	Melting Temperature (ºC)	Creep / Fatigue	Wettability
Sn-Pb	Sn-37Pb	183	–	–
Sn-Cu	99.3Sn-0.7Cu	227	superior than Sn-Pb	inferior copper wetting (compared with eutectic Sn-Pb)
Sn-Ag-Cu	95.5Sn-4.0Ag-0.5Cu	217-219	–	inferior copper wetting (compared with eutectic Sn-Pb)

Source: Angela Grusd and Chris Jorgensen. “Lead-FREE Alloys: Fitting the Square Peg in the Square Hole”, Circuitree, September 1999.

Table F.3.7: Performance of Lead-free Alloys, Summary Table

Alloy Family	Alloy Composition	Melting Range (ºC)	Liquidus Temperature	Wave Soldering	Reflow Soldering	Reliability*
Sn-Cu	Sn-0.7Cu	227	–	optimum	undesirable	–
Sn-Ag-Cu	Sn-3.6Ag-0.9Cu	216-217	~220	–	–	–
	Sn-3.8Ag-0.7Cu	–	~220	–	optimum	similar to / superior than Sn-Pb and Sn-Pb-Ag

Source: Jasbir Bath et al., “Research Update: Lead-Free Solder Alternatives”, National Electronics Manufacturing Initiative (NEMI), Circuits Assembly (www.circuitassembly.com), May 2000.

* Reliability testing was carried out from -20 to 125ºC for up to 3,000 cycles; and power cycling from 25 to 110ºC for 5,000 cycles.

Table F.3.8: Lead-Free Alloys during Wave Soldering and in SMT Applications, Summary Table

Alloy Family				
Alloy Composition		Sn-0.7Cu	Sn-3.8-4.0Ag-0.5-0.7Cu (TSC-4)	
Melting Temperature (ºC)		227	217-218	217-218
Wave Soldering	**Dross Production**	–	less than other alloys	less than other alloys
	Wetting Properties	–	good	good
	Joint Reliability	–	superior	superior
SMT Applications	**Joint Reliability**	–	excellent	excellent
	Mechanical Fatigue Resistance	–	excellent	excellent
Comments		used for high temperature lead-free applications	no-clean solder pastes pass Bellcore and IPC specifications	falls under JEIDA recommendation; no-clean solder pastes pass Bellcore and IPC specifications

Source: AIM - Technical Data Sheet (http://www.aimsolder.com/leadfree_tdss.cfm?section=assembly)

Table F.3.9: Thermal and Mechanical Properties of Lead-free Alloys, Summary Table

Property		**Alloy Composition**	
		Sn-0.7Cu	**Sn-4Ag-0.5Cu**
Melting Temperature		227	218
Relative Wetting Properties		poor	weaker & slower than CASTIN®* (lower-Ag content alloy)
Relative Thermal Properties**	**Joint Strength**	poor	good
	Fatigue Resistance	poor	superior
Mechanical Strength - Flex Testing***		failed (cracked solder joints)	passed

Source: Karl Seelig and David Suraski, “Materials and Process Considerations for Lead-Free Electronics Assembly”

* The CASTIN® alloy (Sn-2.5Ag-0.8Cu-0.5Sb), consists of the ternary alloy with the addition of a grain -refining and melting temperature-decreasing dopant.

** Test boards were built using each the alloy in conjunction with 1206 thin film resistors. Thermal shock ranged between -40 to 125ºC for 300, 400 and 500 15-minute cycles.

*** Test boards were built using each alloy in conjunction with 1206 thin film resistors and were subjected to flex testing.

Table F.3.10.a: Mechanical Properties of Lead-free Alloys Compared With Eutectic Sn-37Pb, Summary Table

Physical and Mechanical Properties								
Alloy Family		**Sn-Pb**	**Sn-Cu**	**Sn-Ag-Cu**			**Sn-Ag-Cu-Bi**	
Alloy Composition		Sn-37Pb	Sn-0.7Cu	Sn-3.5Ag-0.7Cu	Sn-3.8Ag-0.7Cu	Sn-4Ag-0.5Cu	Sn-2Ag-0.5Cu-7.5Bi	Sn-3Ag-3Cu-2Bi
Density (g/cm^3)		8.4	7.3	–	7.5	7	8	–
Melting Point (ºC)		183	227-240	–	217	217-218	186-212	–
Specific Heat (J/g)		45	–	–	–	–	–	–
CTE (μm per m.ºC)		19	–	–	–	–	–	–
Electrical Conductivity (%IACS)*		11.9	13	13	13	–	–	–
Electrical Resistivity (μO-cm)		14.5	10-15	–	13	–	–	10.6
Brinell Hardness (HB) or Vickers Hardness (VHN)		17 (HB)	–	–	15 (HB)	–	–	34.5 (VHN)
Wettability Ratio		95, 91	–	–	–	–	–	97, 96
Tensile Strength (20ºC) (N/mm^2 at Strain Rate 0.004 s^{-1})		40	–	48	48	–	–	–
Stress to Rupture	**+/- 5 N/mm^2**	–	4,300	–	–	–	–	–
	+/- 10 N/mm^2	–	1,460	–	–	–	–	–
Joint Shear Strength (N/mm^2 at 0.1 mm/min)	**20ºC**	23	23, 20	–	27	–	–	–
	100ºC	14	16, 21	–	17	–	–	–
Creep Strength (N/mm^2 at 0.1 mm/min)	**20ºC**	3.3	8.6	13	13.0	–	–	–
	100ºC	1.0	2.1	5	5.0	–	–	–

Source: NIST and CSM, "Database for Solder Properties with Emphasis on New Lead-free Solders", February 2002, (http://www.boulder.nist.gov/div853/lead%20free/props01.html)

CTE: Coefficient of Thermal Expansion

* 100%IACS = 58.00MS/m

Table F.3.10.b: Mechanical Properties of Sn-0.7Cu, Sn-3.2Ag-0.8Cu and Eutectic Sn-37Pb, Summary Table

Alloy Family	Alloy Composition	Process*	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Uniform Elongation (%)	Total Elongation (%)
Sn-Pb	Sn-37Pb	–	27.2	30.6	3	48
Sn-Cu	Sn-0.7Cu	water quenched (average)	15	19	5.4	20.8
		air cooled	16	22	9.1	41.2
Sn-Ag-Cu	Sn-3.2Ag-0.8Cu	water quenched (average)	28	32	3.4	22.1
		air cooled	20	30	6.2	26.1

Source: NIST and CSM, “Database for Solder Properties with Emphasis on New Lead-free Solders”, February 2002, (http://www.boulder.nist.gov/div853/lead%20free/props01.html)

* Two processes were carried out: water quenched and air cooled. Four runs were carried out for the water quenched process and the results were averaged.

Table F.3.10.c: Strength, Ductility and Tensile Properties of Lead-Free Solder Alloys Compared with Eutectic Sn-Pb Alloy, Summary Table

Strength, Ductility and Tensile Properties							
Alloy Family		**Sn-Pb**	**Sn-Cu**	**Sn-Ag-Cu**		**Sn-Ag-Bi-Cu**	
Alloy Composition		Sn-37Pb	Sn-3Cu	Sn-0.5Ag-4Cu	Sn-3Ag-4Cu	Sn-2Ag-7.5Bi-0.5Cu	Sn-2Ag-46Bi-4Cu
Elastic Modulus	**GPa**	15.7	–	–	–	–	–
0.2% Yield Strength	**psi**	3,950	–	3,724	6,276	12,370	9,806
	MPa	27.2	–	25.7	43.3	85.3	67.6
Tensile Strength	**psi**	4,442	6,420	4,312	7,006	13,440	10,070
	MPa	30.6	–	29.7	48.3	92.7	69.4
Relative Elongation (Total)	**%**	48	–	27	22	12	3
Strength Coefficient	**psi**	4,917	–	–	–	–	–
	a	33.9	–	–	–	–	–
Hardening Exponent		0.033	–	–	–	–	–

Source: NIST and CSM, “Database for Solder Properties with Emphasis on New Lead-free Solders”, February 2002, (http://www.boulder.nist.gov/div853/lead%20free/props01.html)

Table F.3.10.d: Shear Strengths, Solidus and Liquidus Temperatures, and Wetting Angles, Summary Table

Alloy Family	Alloy Composition	Shear Strength (MPa)*			Temperature		Wetting Angle (degrees)
		Test Temperature			Solidus (ºC)	Liquidus (ºC)	
		22ºC	22ºC	170ºC			
		Cooling Rate**					
		1.5 º/s	10 º/s	10 º/s			
Sn-Pb	Sn-37Pb	–	–	–	183	183	–
	Sn-40Pb	37.4	36.5	4.5	183	188	17
Sn-Cu	Sn-0.7Cu	–	29.8	10.1	227	–	–
Sn-Ag-Cu	Sn-3.6Ag-1Cu	54	67	24.4	217	217.9	–
	Sn-3.8Ag-0.7Cu	–	63.8	25.1	217	–	–
	Sn-4.7Ag-1.7Cu	47	58	21.6	217	–	21

Source: NIST and CSM, “Database for Solder Properties with Emphasis on New Lead-free Solders”, February 2002, (http://www.boulder.nist.gov/div853/lead%20free/props01.html)

* Cross-head speed: 0.1 mm/min; gap thickness: 76.2 µm

** Cooling rate in soldering (test) but joints

Table F.3.10.e: Thermal Properties of Candidate Lead-Free Solders, Summary Table

Alloy Family	Alloy Composition	Liquidus Temperature (ºC)	Reflow Temperature (ºC)	Melting Range (ºC)
Sn-Cu	Sn-0.7Cu	227	245-255	227
Sn-Ag-Cu	Sn-3.2Ag-0.5Cu	218	238-248	217-218
	Sn-3.5Ag-0.75Cu	218	238-248	–
	Sn-3.8Ag-0.7Cu	220	238-248	217-220
	Sn-4Ag-0.5Cu	–	–	217-225
	Sn-4Ag-1Cu	220	238-248	217-220
Sn-Ag-Cu-Bi	Sn-3.5Ag-0.7Cu-5Bi	–	–	198-213
	Sn-3.2Ag-1.1Cu-3Bi	240	230-240	–

Source: NIST and CSM, “Database for Solder Properties with Emphasis on New Lead-free Solders”, February 2002, (http://www.boulder.nist.gov/div853/lead%20free/props01.html)

Table F.3.10.f: Ternary Sn-Ag-Cu Elastic Properties vs. Temperature, Summary Table

Elastic Property		**Test Temperature (ºC)**				
		-25	**25**	**75**	**125**	**160**
Yield Stress As-Cast (MPa)	**Minimum**	41.51	30.13	16.45	13.47	9.63
	Mean	41.645	31.835	20.975	13.635	10.19
	Maximum	41.78	33.54	25.5	13.8	10.75
Yield Stress Aged (MPa)	**Minimum**	36.77	21.21	16.97	10.71	10.79
	Mean	38.655	21.925	17.005	12.15	11.35
	Maximum	40.54	22.64	17.04	13.59	11.91
Elastic Modulus As-Cast (MPa)	**Minimum**	2863.6	4956.5	4021.6	2836.8	2217.3
	Mean	3978.3	5357.75	4455.5	3837.25	3309.05
	Maximum	5093	5759	4889.4	4837.7	4400.8
Elastic Modulus Aged (MPa)	**Minimum**	3415.9	3828.7	3752.6	2742.4	2715.7
	Mean	3495.95	4312.55	4004.8	3336.3	3663.7
	Maximum	3576	4796.4	4257	3930.2	4611.7
Yield Strain As-Cast (MPa)	**Minimum**	0.011	0.008	0.0053	0.0045	0.0047
	Mean	0.01505	0.00845	0.0062	0.00565	0.0056
	Maximum	0.0191	0.0089	0.0071	0.0068	0.0065
Yield Strain Aged (MPa)	**Minimum**	0.0165	0.0067	0.0058	0.0054	0.0049
	Mean	0.0178	0.00715	0.00615	0.00555	0.0055
	Maximum	0.0191	0.0076	0.0065	0.0057	0.0061

Source: NIST and CSM, “Database for Solder Properties with Emphasis on New Lead-free Solders”, February 2002, (http://www.boulder.nist.gov/div853/lead%20free/props01.html)

F.4 QUALITATIVE PERFORMANCE RESULTS

Alloy Composition*	Comments	Reference
Tin-Copper		
Eutectic Sn-Cu	▸ Has the highest melting temperature. ▸ Is lower in tensile strength and higher in elongation than Sn-Ag and Sn-Pb. ▸ Shear strength is comparable with Sn-Pb. ▸ Creep strength is higher than 100Sn but lower than Sn-Ag-Cu (at 20 and 100ºC). ▸ Time to rupture is higher than Sn-Ag-Cu but lower than Sn-40Pb (at 25 and 100ºC). ▸ Wetting properties can potentially replace Sn-Pb in wave and reflow processes. ▸ Reflow spreading is better than Sn-Ag but poorer than eutectic Sn-Pb. ▸ Is good for wave soldering. ▸ Wettability (when using an unactivated flux) is lower than Sn-Pb. ▸ Has fairly good fatigue resistance.	Lau et al.
Sn-Cu	▸ Tensile strength drops with increasing temperatures. ▸ Is weaker and more ductile than Sn-Ag-Cu and Sn-Pb. ▸ Creep performance of Sn-0.5Cu is similar to Sn-37Pb and poorer than Sn-Ag-Cu at 75ºC.	Plumbridge, William J.
Sn-0.7Cu	▸ Is suitable for high-temperature applications. ▸ Creep/fatigue data is superior to Sn-Pb but inferior to Sn-Ag-*X*.	Grusd, Angela and Chris Jorgensen
Sn-0.7Cu	▸ Is the best choice for wave soldering (along with Sn-3.5Ag). ▸ Is undesirable for reflow applications. ▸ Is similar to eutectic Sn-37Pb for surface-mount use.	Bath et al.
Sn-Cu	▸ High melting temperature prohibits alloy use for temperature-sensitive applications. ▸ Demonstrates poor wetting alloy (as compared with other lead-free solders). ▸ Has a low capillary action to draw it into barrels during PTH technology. ▸ Has poor overall fatigue characteristics. ▸ Lacks the fatigue resistance needed for surface mount. ▸ Cracked during mechanical strength-flex testing indicating a weak joint unable to withstand a wide range of mechanical stresses.	Seelig, Karl and David Suraski
Sn-0.7Cu	▸ Is cost-effective. ▸ Is a good alternative for wave soldering and hand soldering applications. ▸ Has poor wetting.	AIM(a)
Sn-3Cu	▸ Recommended for high-temperature applications only.	AIM(a)
Tin-Silver-Copper		
Sn-3.5Ag-0.9Cu	▸ Tensile strength is higher than eutectic Sn-Pb. ▸ Is higher than Sn-Pb in yield strength, shear strength, impact strength, and creep resistance (alloys near eutectic Sn-Ag-Cu). ▸ Tensile strength, shear strength, and melting temperature increases while elongation decreases (alloys further away from eutectic Sn-Ag-Cu). ▸ Demonstrates the longest time to break in creep tests (Sn-3.5Ag-0.75Cu). ▸ Wettability (when using an unactivated flux) is lower than Sn-Pb but higher than Sn-Cu. ▸ Is a prevailing alternative to lead-containing solder.	Lau et al.
Sn-Ag-Cu	▸ Is difficult to plastically deform and less likely to harden. ▸ Fatigue life is longer than Sn-Pb (sufficient fatigue resistance for use in electronics assembly).	Ochiai et al.
Sn-Ag-Cu	▸ Displays the smallest elongation to failure. ▸ Is stronger than Sn-Cu and Sn-Pb. ▸ Has much greater creep resistance than Sn-37Pb. ▸ Has lower creep ductility than Sn-37Pb. ▸ Potentially the most popular lead-free alloy is Sn-3.8Ag-0.7Cu (patented).	Plumbridge, William J.
Sn-3Ag-0.5Cu	▸ Tensile strength decreases with increasing temperature and decreasing strain rate. ▸ Tensile strength is similar to Sn-3.8Ag-0.7Cu, and superior than Sn-3.5Ag and Sn-0.5Cu (at 10^{-3}/s and 348K). ▸ Creep resistance is comparable to Sn-3.8Ag-0.7Cu and superior to Sn-Ag.	Kariya, Yoshiharu and William J. Plumbridge

Tin-Silver-Copper (contd.)		
Sn-3.5Ag-0.5Cu	▸ Mechanical properties are comparable with Sn-37Pb ▸ Has slightly lower ultimate tensile strength and yield strength than Sn-37Pb. ▸ Creep performance is superior to Sn-37Pb. ▸ Wetting properties is comparable to Sn-37Pb. ▸ Has similar static viscosity, dynamic viscosity, tack, printability, solderability, wide reflow window and reflow characteristics as Sn-37Pb. ▸ Has a larger print life than Sn-37Pb. ▸ Alloy paste is usable in PCB applications.	Sheng et al.
Sn-4Ag-0.5Cu	▸ Is well-suited for high operation temperatures (up to 175ºC). ▸ Joint mechanical stability degrades when the melting point is approached. ▸ Does not wet copper as well as eutectic Sn-Pb when using commercial fluxes.	Grusd, Angela and Chris Jorgensen
Sn-3.9Ag-0.6Cu	▸ Is the preferred choice for reflow soldering. ▸ Demonstrates adequate solderability, yet inferior to Sn-Pb. ▸ In line with the International Tin Research Institute alloy range recommendation, thus qualifying for international standards.	Bath et al.
Sn-3Ag-0.5Cu (LF218™)	▸ Has a low melting point for a lead-free alloy. ▸ Lowest cost alloy from the Sn-Ag-Cu family. ▸ Best wetting Sn-Ag-Cu alloy. ▸ Has excellent solder joint reliability. ▸ Is compatible with all flux types. ▸ Has excellent mechanical fatigue resistance. ▸ Is a virtual drop-in for eutectic Sn-Pb in wave and hand soldering applications. ▸ Produces less dross than other solder alloys, wets well, and provides superior joint strength in wave soldering. ▸ Produces stronger solder joints, has greater mechanical fatigue resistance, and is a virtual drop-in for the eutectic Sn-Pb solder in SMT applications. ▸ In line with JEIDA recommendation. ▸ No-clean solder pastes pass all Bellcore and IPC specifications.	AIM(b)
Sn-3Ag-0.5Cu (LF218™)	▸ In line with JEIDA recommendation. ▸ Lowest cost of pure metals for this alloy.	AIM(a)
Sn-3.8-4Ag-0.5-0.7Cu (TSC-4)	▸ Has a low melting point. ▸ Demonstrates good wetting. ▸ Demonstrates excellent solder joint reliability. ▸ Is compatible with all flux types. ▸ Demonstrates excellent mechanical fatigue resistance. ▸ Is a virtual drop-in for the eutectic Sn-Pb solder in SMT applications. ▸ In line with the NEMI recommendation. ▸ No-clean solder pastes pass all Bellcore and IPC specifications.	AIM(b)
Sn-3.8-4Ag-0.5-0.7Cu (TSC-4)	▸ Demonstrates similar characteristics as CASTIN® and LF218™. ▸ Higher cost of metals than CASTIN® and LF218™. ▸ Presents a potential silver phase change issues.	AIM(a)
Sn-3.5Ag-0.5Cu	▸ Has similar characteristics to Sn-3Ag-0.5Cu ▸ Is slightly higher cost of metals then Sn-3Ag-0.5Cu.	AIM(a)
Sn-4Ag-0.5Cu	▸ Demonstrates good fatigue characteristics (superior thermal fatigue resistance as compared to Sn-Cu). ▸ Has good overall joint strength. ▸ Exhibits some change in grain structure during thermal cycling. ▸ Passed all mechanical strength-flex test requirements. ▸ Sufficient supply of base materials.	Seelig, Karl and David Suraski

Tin-Silver-Copper-Bismuth		
Sn-Ag-Cu-Bi	‣ Surface tension, electrical resistivity, and density are comparable with Sn-Ag, Sn-Ag-Cu and Sn-Ag-Cu-*X*. ‣ Demonstrates superior hardness to Sn-Pb. ‣ Has higher tensile and yield strengths, lower elongation, and a slower creep rate than Sn-Pb. ‣ Wetting behavior is fairly comparable with Sn-37Pb (with 1 or 2% Bi-content). ‣ Outstanding in creep resistance and wetting.	Lau et al.

* Several literature sources cited select characteristics for alloys that differed in composition from that mentioned. Such compositions have been included in parentheses following the appropriate comment.

F.5 REFERENCES

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APPENDIX G:
LIFE-CYCLE INVENTORY FUEL DATA

Table G-1. Fuel conversion factors

Fuel	**Heat Value (H) (MJ/L)**	**Reference**	**Density (D) (kg/L)**	**Reference**
Diesel Fuel	35.875	(1)	0.845	(5)
Heavy fuel oil #6 (residual)	38.579	(1)	0.944	(2)
Light fuel oil #2 (distillate)	36.739	(1)	0.843	(2)
Liquified petroleum gas (LPG)	23.276	(1)	0.542	(2)
Natural Gas	0.034	(3)	7.58×10^{-4}	(4)

References:

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APPENDIX H:
EXAMPLE TOXICITY CALCULATIONS

APPENDIX H:

EXAMPLE TOXICITY CALCULATION

The following example illustrates how toxicity impacts are calculated. Please refer to Section 3.2.11 of the LFSP report for descriptions of the methodologies for calculating these impacts.

If two toxic chemicals (e.g., toluene and benzo(a)pyrene) are included in a waterborne release to surface water from Process A, impact scores would be calculated for the following impact categories (based on the classification shown in Table 3-1):

- Chronic public health effects, cancer and non-cancer; and,
- Aquatic ecotoxicity.

Despite the output types being waterborne releases, the water eutrophication and water quality impact categories are not applicable here because the chemical properties criteria in Table 3-1 are not met. That is, these chemicals do not contain N or P and are not themselves wastewater streams.

Using chronic public health effects as an example, impact scores are then calculated for each chemical as follows:

Cancer effects:

$$IS_{CHP\text{-}CA:toluene} = HV_{CA:toluene} \times Amt_{TCoutput:toluene}$$

$$IS_{CHP\text{-}CA:benzo(a)pyrene} = HV_{CA:benzo(a)pyrene} \times Amt_{TCoutput:benzo(a)pyrene}$$

Non-cancer effects:

$$IS_{CHP\text{-}NC:toluene} = HV_{NC:toluene} \times Amt_{TCoutput:toluene}$$

$$IS_{CHP\text{-}NC:benzo(a)pyrene} = HV_{NC:benzo(a)pyrene} \times Amt_{TCoutput:benzo(a)pyrene}$$

Table H-1 presents toxicity data for the example chemicals from Appendix E. The hazard values and impact scores are calculated as follows:

Table H-1. Toxicity data used in example calculations

Chemical	**Cancer**		**Chronic non-cancer effects**	
	Weight of evidence	**Slope factor (SF) (mg/kg-day)$^{-1}$**	**Oral (mg/kg-day)**	**Inhalation (mg/m^3)**
Toluene	D, 3	None	100 (NOAEL)	411.1 (NOAEL)
Benzo(a)pyrene	B2, 2A	7.3 (oral) 3.1 (inhalation)	No data	No data

Cancer effects:

The cancer HV for benzo(a)pyrene is calculated as follows:

$$\textbf{Oral:}\quad (HV_{CA\ oral})_i = \frac{1/(oral\ NOAEL_i)}{1/(oral\ NOAEL_{mean})}$$

$HV_{CAoral:benzo(a)pyrene}$ $= 7.3\ (mg/kg\text{-}day)^{-1} \div 0.71\ (mg/kg\text{-}day)^{-1}$
$= 10.3$

$$\textbf{Inhalation:}\quad (HV_{CA\ inh})_i = \frac{inhalation\ SF_i}{inhalation\ _{Sfmean}}$$

$HV_{CAinhalation:benzo(a)pyrene}$ $= 3.1\ (mg/kg\text{-}day)^{-1} \div 1.7\ (mg/kg\text{-}day)^{-1}$
$= 1.82$

Thus, the cancer HV is 10.3, the greater of the two values. The cancer HV for toluene is zero since it has no slope factor and a WOE classification of D (EPA) and 3 (IARC).

Given a hypothetical waterborne release amount of 0.1 kg of benzo(a)pyrene per functional unit, the impact score for benzo(a)pyrene cancer effects is given by:

$IS_{CHP\text{-}CA,W:benzo(a)pyrene}$ $= 10.3 \times 0.1$
= 1.03 kg cancertox-equivalents of benzo(a)pyrene per functional unit

Toluene's impact score for cancer is zero since its HV is zero.

Non-cancer effects:

Since no data are available for non-cancer effects of benzo(a)pyrene, a default HV of one is assigned, representative of mean toxicity.

The non-cancer HV for toluene is calculated as follows:

$$\textbf{Oral:}\quad (HV_{NC\ oral})_i = \frac{1/(oral\ NOAEL_i)}{1/(oral\ NOAEL_{mean})}$$

$= 1/100\ mg/kg\text{-}day \div 1/14.0\ mg/kg\text{-}day$
$= 0.140$

Inhalation: $$(HV_{NC\ inhalation})_i = \frac{1/(inhal\ NOAEL_i)}{1/(inhal\ NOAEL_{mean})}$$

$$= 1/411.1\ mg/m^3 \div 1/68.7\ mg/m^3$$
$$= 0.167$$

Thus, the non-cancer HV for toluene is 0.167, the greater of the two values.

Given the following hypothetical output amounts:

$Amt_{TC\text{-}O:TOLUENE}$ = 1.3 kg of toluene per functional unit
$Amt_{TC\text{-}O:BENZO(A)PYRENE}$ = 0.1 kg of benzo(a)pyrene per functional unit

The resulting non-cancer impact scores are as follows:

$IS_{CHP\text{-}NC,W:TOLUENE}$ = 0.167 x 1.3
= 0.22 kg non-cancer-equivalents of toluene per functional unit

$IS_{CHP\text{-}NC,W:BENZO(A)PYRENE}$ = 1 x 0.1
= 0.1 kg non-cancer-equivalents of benzo(a)pyrene per functional unit

If these were the only outputs from Process A relevant to chronic public health effects, the total non-cancer impact score for this impact category for Process A would be:

$IS_{CHP\text{-}NC:PROCESS\_A}$ = $IS_{CHP\text{-}NC\text{-}W:TOLUENE} + IS_{CHP\text{-}NC\ \text{-}W:BENZO(A)PYRENE}$
= 0.22 + 0.1
= 0.23 nkg non-cancertox-equivalents per functional unit for Process A.

If the product system Y contained three processes altogether (Processes A, B, and C), and the non-cancer impact scores for Process B and C were 0.5 and 1.0, respectively, impact scores would be added together to yield a total impact score for the product system relevant to chronic public non-cancer health effects:

$IS_{CHP\text{-}NC:PROFILE\_Y}$ = $IS_{CHP\text{-}NC:PROCESS\_A} + IS_{CHP\text{-}NC:PROCESS\_B} + IS_{CHP\text{-}NC:PROCESS\_C}$
= 0.23 + 0.5 + 1.0
= 1.73 kg non-cancertox-equivalents per functional unit for Profile Y.

An environmental profile would then be the sum of all the processes within that profile for each impact category.