United States
Environmental Protection
Agency

Solders in Electronics: A Life-Cycle Assessment Summary

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This summary document is based on information presented in the project report, *Solders in Electronics: A Life-Cycle Assessment*, written by the University of Tennessee under a grant from EPA. Some information in the Life Cycle Assessment was provided by individual technology vendors and has not been independently corroborated by EPA. The identification of specific products or processes in this document is not intended to represent an endorsement by EPA or the U.S. Government. This summary document has not been through a formal external peer review process.

Design for the Environment
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Introduction

This report summarizes the results of an analysis conducted by the University of Tennessee's (UT) Center for Clean Products and Clean Technologies for the U.S. Environmental Protection Agency's Design for the Environment (DfE) Lead-Free Solder Partnership (LFSP). The DfE LFSP is a voluntary, cooperative partnership among the DfE Program, UT, the IPC–Association Connecting Electronics Industries (IPC), the Electronic Industries Alliance (EIA), several individual electronics companies, and other interested parties. The partnership assessed the environmental life-cycle impacts of selected lead-free solders as alternatives to tin-lead solder. The DfE LFSP analysis also provides an assessment of the recyclability and leachability of the solders.

Purpose and Scope of the Study

The purpose of the lead-free solder study is threefold:

1. to evaluate the life-cycle environmental impacts of selected lead-based and lead-free solder alternatives using life-cycle assessment (LCA)
2. to evaluate the effects of lead-free solders on leachability, recycling, and reclamation at the end-of-life
3. to identify data gaps or other potential areas of analysis for future investigation by EPA or industry

This study used LCA to evaluate both lead-based and lead-free solder alternatives. LCAs, which are generally global and non-site specific in scope, look at the full life cycle of the product being evaluated, from materials acquisition to manufacturing, use, and end-of-life (i.e., final disposition). The LFSP LCA considers impacts related to material consumption, energy use, air resources, water resources, landfills, human toxicity, and ecological toxicity, as well as leachability and recycling.

Need for the Study

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; however, concern over lead's relatively high toxicity to human health and the environment and ensuing international market and legislative pressures have led the U.S. electronics industry to begin switching to lead-free solders. Although the performance of the metals and fluxes of many of the alternatives has been studied, their life-cycle environmental impacts have not yet been evaluated. The LFSP offers the opportunity to mitigate current and future risks by helping the electronics industry to identify lead-free solders that are less toxic and that pose the fewest risks over their life cycles. The LFSP study also allows the electronics industry to make environmentally informed choices when assessing and implementing improvements, such as changes in product, process, and activity design, raw material use, industrial processing, consumer use, and waste management. Additionally, many other organizations and individuals in the U.S. and abroad have expressed interest in obtaining objective, detailed information about the life-cycle impacts of selected lead-free solders.

About EPA's Design for the Environment Program

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. DfE industry projects are cooperative, joint partnerships with trade associations, businesses, public-interest groups, and academia to assist businesses in specific industries to identify and evaluate more environmentally sound products, processes, and technologies. The DfE Lead-Free Solder Partnership consisted of members of electronics industry trade associations, circuit board assemblers, solder suppliers, academic institutions, and EPA. The direction and focus of this project was determined by the project partners.

Approximately 176 million pounds of lead-based solder were used world-wide in 2002. Electronics in the U.S. 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. The European Restriction of Hazardous Substances in Electrical and Electronic Equipment (RoHS) Directive (2002/95/EC) stipulates that lead and other selected toxic chemicals in electrical and electronic equipment be replaced by July 2006. In Japan, subsequent to take back (recycling) legislation that took effect in that country in 2001, the Japanese Ministry of the Environment and the Ministry of Economy, Trade and Industry suggested a voluntary phase-out of lead, along with increased end-of-life (EOL) product recycling. Consumer demand for lead-free products may also increase as the general public becomes more aware of lead issues. All of these forces combine to drive the U.S. electronics market inexorably toward lead-free solders. Managing the environmental impacts posed by this change is crucial to the long-term environmental sustainability of both the U.S. and global electronics industries. Using this evaluation, the U.S. electronics industry will 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 be better able to meet the competitive challenges of the world market. In addition, the LCA model and associated results provide a baseline upon which solder alternatives not included in the study can potentially be evaluated. This will allow for further expedited LCA studies.

This booklet summarizes the key findings of the DfE Lead-Free Solder Partnership study. The information is presented in ten sections that summarize the following:

- the study's life-cycle assessment methodology;
- the environmental and health impacts of the solders evaluated;
- the limitations of the study and alternative data analyses;
- steps circuit board manufacturers can take to reduce environmental and health impacts;
- challenges to implementing lead-free soldering; and
- information on cost and performance differences among the solder.

For more detailed information on any of these topics, the reader is encouraged to reference the full project report, *Lead-Free Solders: A Life-Cycle Assessment* (Geibig and Socolof, 2005). The document may be viewed at www.epa.gov/dfe.

Question 1:
What is a life-cycle assessment?

The DfE Lead-Free Solder Partnership (LFSP) conducted this analysis of selected lead-based and lead-free solder alternatives using a life-cycle assessment (LCA) approach, which allowed for a comprehensive analysis of the environmental consequences of a product system over its entire life. LCA, which is increasingly being used by industry, contains four major steps as defined by the Society of Environmental Toxicology and Chemistry (SETAC) and more recently by the International Standards Organization (ISO):

1. **Goal Definition and Scoping** lays out the rationalization for conducting the LCA and its general intent, as well as specifying the product systems and data categories to be studied.
2. **Life-Cycle Inventory** (LCI) involves the quantification of raw material and fuel inputs, and solid, liquid, and gaseous emissions and effluents.
3. **Life-Cycle Impact Assessment** (LCIA) characterizes the environmental burdens identified in the LCI and assesses their effects on human and ecological health, as well as other abiotic effects, such as smog formation and global warming.
4. **Improvement Assessment or Interpretation of Results** uses findings from the analysis to identify and evaluate opportunities for reducing life-cycle environmental impacts of a product, process, or activity, or to reach conclusions and provide recommendations. SETAC's definition includes the improvement assessment component, whereas ISO includes the life-cycle interpretation component. The LFSP LCA did not perform this step; it is left to the electronics industry and others to complete this step for their specific operation or interests using the results of this study.

LCA evaluates the life-cycle environmental impacts from each of five 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., material 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. The LFSP LCA combines raw materials extraction and materials processing into one "upstream" life-cycle stage in the presentation of results.

Figure 1.1. Life-Cycle Stages for Solder Alternatives

INPUTS	LIFE-CYCLE STAGES	OUTPUTS
	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 →	**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.	→ Wastes
Energy →	**PRODUCT MANUFACTURE** Processing materials into solder and solder alternatives.	
Resources →	**PRODUCT USE** (USE/APPLICATION) Application of the solders onto printed wiring boards, which are then incorporated into various electronics products.	→ Products
	FINAL DISPOSITION (END-OF-LIFE) At the end of their useful lives, the solders, which are part of another product that is 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 and/or disposed of.	

Question 2:
Which solders were investigated during the project?

Both paste and bar solders were evaluated in this study. Paste solders are screened onto printed wiring boards (PWBs) to facilitate placement of components, then reflowed by passing the PWB 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. 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 feed-through components. Wave soldering is used mostly in low-tech, low-cost applications, and reflow soldering is usually used for higher-tech applications. Table 2.1 lists the specific solders that were investigated in this study.

Table 2.1. Solders Selected for Evaluation

Solder alloys	Makeup (%)	Density (g/cc)	MP (°C)	Application type
Tin/Lead (SnPb, baseline)	63 Sn / 37 Pb	8.4	183	Reflow and Wave
Tin/Copper (SnCu)	99.2 Sn / 0.8 Cu	7.3	227	Wave
Tin/Silver/Copper (SAC)	95.5 Sn / 3.9 Ag / 0.6 Cu	7.35	218	Reflow and Wave
Bismuth/Tin/Silver (BSA)	57.0 Bi / 42.0 Sn / 1.0 Ag	8.56	138	Reflow
Tin/Silver/Bismuth/Copper (SABC)	96.0 Sn / 2.5 Ag / 1.0 Bi / 0.5 Cu	7.38	215	Reflow

The project participants chose the individual solders based on a variety of factors, such as current market trends and solder performance studies; all of the solders are currently available for use in the electronics industry. Eutectic tin/lead (SnPb) solder, the only lead-based solder that was evaluated, was chosen as the baseline for both wave and reflow applications. 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 wave solder and reflow environment and because it appears to be emerging, through testing, as a top choice for a substitute for SnPb (NEMI, 2002). The evaluation group also includes two bismuth-containing solders—bismuth/tin/silver (BSA) and tin/silver/bismuth/copper (SABC)—in order to assess their environmental impacts, particularly at the end-of-life, because they are being considered by the industry partners as possible replacements for lead-based solder.

Functional Unit

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. 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. Thus, a volume of one thousand cubic centimeters of solder was selected for use as the functional unit in the LCA.

QUESTION 3:
How were life-cycle environmental and health impacts evaluated?

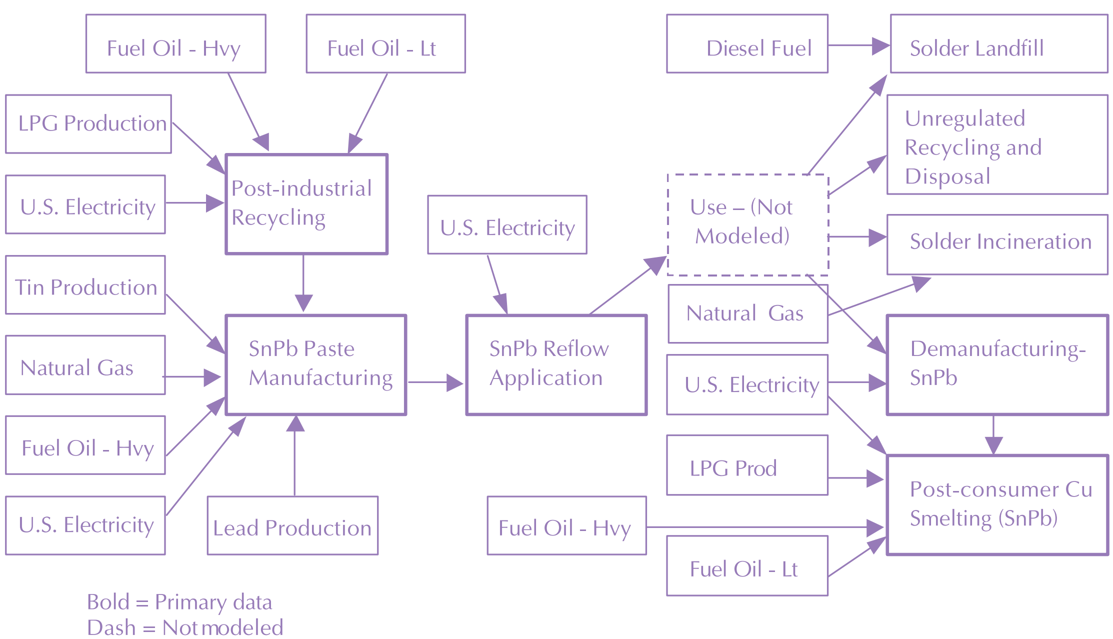
Two of the phases of an LCA, life-cycle inventory and life-cycle impact assessment, are necessary to calculate environmental impacts.

LIFE-CYCLE INVENTORY

Life-cycle inventory (LCI) involves identifying and quantifying material and resource inputs, and emission and product outputs, from the product being evaluated. For the LFSP, LCI inputs include materials, energy, and other resources used throughout the life cycle of the solders. Outputs include products, air emissions, water effluents, and releases to land. Figure 3.1 shows the processes that are included in the scope of the LFSP for the SnPb paste solder life cycle. Although the process diagrams for solder alternatives may vary somewhat from solder to solder and from paste to bar, the scope for each alternative is similar to that shown for the SnPb paste solder, except for the following differences:

1. The upstream production of lead is replaced with the appropriate alternate metals found in each alloy.
2. In addition to the fuels used in paste manufacturing (i.e., natural gas, heavy fuel oil), liquefied petroleum gas (LPG) is also used as a fuel input in bar manufacturing.
3. The cost of copper smelting for the BSA alloy is potentially prohibitive because of its high bismuth content. Therefore, flows from demanufacturing are assumed to be sent to a landfill or an incinerator rather than to a copper smelter.

Figure 3.1. SnPb Paste Solder Life-Cycle Processes



Given the enormous amount of data involved in inventorying all of these inputs and outputs, decision rules were used to determine what to include in the LCI. Decision rules are designed to make data collection manageable, but still representative of the product and its impacts. For example, upstream process inputs in major processes that meet one or more of the following criteria would be included in this study:

- constitutes greater than one percent of the total mass or energy required to manufacture the solder;
- materials falling into the one to five percent range were evaluated based on the other decision rule criteria, as well as the availability of data;
- is known or suspected to have environmental significance;
- is known or suspected to have significant energy requirements;
- is physically unique to a solder alternative over the baseline SnPb solder; or
- is functionally significant to the solder.

The data collected for this study included primary data that were obtained for this project, data obtained through site visits, and testing or secondary data that were obtained from existing databases. 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 solders.

Life-Cycle Impact Assessment

Life-cycle impact assessment (LCIA) is the process by which the environmental burdens identified in the LCI are translated into environmental impacts. It is important to note that direct comparisons cannot be made across impact categories, because impacts in different impact categories are generally calculated based on different scales. The LFSP LCIA consisted of two steps: classification and characterization.

Classification

The LCIA methodology employed in this study places each impact and output from the LCI into one or more of sixteen impact categories, including global warming, stratospheric ozone depletion, photochemical smog, energy consumption, potential chronic human health, and aquatic ecotoxicity.

Characterization

The characterization step of LCIA converts and aggregates LCI results to common units within an impact category to produce an impact score. Three different approaches are used to quantify the magnitude of potential impacts, depending on the impact category:

- **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)].

- **Scoring of inherent properties:** An impact score is based on the inventory amount weighted by a score representing a certain effect for a specific material (e.g., toxicity impacts are weighted using a toxicity scoring method).

Table 3.1 presents the 16 impact categories and a description of how each is calculated.

Table 3.1. Impact Categories

Impact category	Inventory type: Input	Inventory type: Output	Description
NATURAL RESOURCE IMPACTS			
Non-renewable resource use/depletion	Material, fuel	—	Materials, such as metals or fossil fuels, that are not regenerated naturally.
Renewable resource use	Material, water	—	Materials found in nature that are replenished through natural processes.
Energy use	Electricity, fuel	—	The amount of energy consumed. The impacts associated with energy are included under other impact categories.
Landfill space use	—	Solid/hazardous/ radioactive waste to landfill	The volume of landfill space required for solid/hazardous/radioactive waste.
ABIOTIC ECOSYSTEM IMPACTS			
Global warming	—	Air	The mass of greenhouse gases emitted (chemical amounts are weighted according to their potency relative to carbon dioxide).
Stratospheric ozone depletion	—	Air	The mass of ozone depleting chemicals emitted (chemical amounts are weighted according to their potency relative to CFC-11).
Photochemical smog	—	Air	The mass of smog-producing chemicals emitted (chemical amounts are weighted according to their potency relative to ethene).
Acidification	—	Air	The mass of acidifying chemicals emitted (chemical amounts are weighted according to their potency relative to sulfur dioxide).
Air particulates	—	Air	The mass of particulates emitted that have an aerodynamic diameter less than 10 micrometers. Note: also use TSP/dust only when PM_{10}[a] is not available.
Water eutrophication (nutrient enrichment)	—	Water	The mass of eutrophication chemicals released (chemical amounts are weighted according to their potency relative to phosphate).
Water quality	—	Water	The mass of BOD and TSS[a]
HUMAN HEALTH AND ECOTOXICITY			
Chronic, non-carcinogenic human health effects—occupational	Material	—	Weighted score based on the amount and toxicity of non-carcinogenic releases affecting workers.
Carcinogenic human health effects—occupational	Material	—	Weighted score based on the amount and toxicity of carcinogenic releases affecting workers.
Chronic, non-carcinogenic human health effects—public (and terrestrial ecotoxicity)	—	Air, soil, water	Weighted score based on the amount and toxicity of carcinogenic releases affecting the general public.
Carcinogenic human health effects—public	—	Air, soil, water	Weighted score based on the amount and toxicity of carcinogenic releases affecting the general public.
Aquatic ecotoxicity	—	Water	Weighted score based on the amount and toxicity of releases affecting fish.

[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).

Question 4:
How do the environmental and health impacts compare among paste solders?

This section compares the results for each impact category described in Question 3 for the paste solders. Although some LCAs assign importance ranks or weights to impact categories, this LCA does not include this step because it requires subjective choices that might not be appropriate for all stakeholders.

Which Solder Scored Highest and Lowest in Each Impact Category?

Table 4.1 presents the life-cycle impact scores for each of the paste solders evaluated and a quality rating given to each impact category score. Highlights from the results are as follows:

- Among all of the solders,
  - SnPb has the highest impact category score (shown in bold) for six impact categories;
  - SAC has the highest impact category score in ten impact categories;
  - SnPb has the lowest impact category score (shaded values) in five impact categories; and
  - BSA has the lowest impact category score in seven impact categories.

Table 4.1. Paste Solder Life-Cycle Impact Scores

Impact Category	Units per functional unit[a]	Quality Rating[b]	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 use	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
Stratospheric 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
Air particulates	kg	M-H	4.52E-01	**1.30E+00**	5.85E-01	1.01E+00
Water 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 health–non-cancer	kg noncancertox-equiv.	M-H	**5.60E+05**	8.12E+03	2.34E+03	5.25E+03
Occupational health–cancer	kg cancertox-equiv.	L-M	**7.62E+01**	7.20E+01	6.34E+01	7.23E+01
Public human health–non-cancer	kg noncancertox-equiv.	M-H	**8.80E+04**	1.05E+04	5.01E+03	7.84E+03
Public human health–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

[a]The functional unit is 1,000 cc of solder applied to a printed wiring board.

[b]Quality summarizes the overall relative data quality associated with each impact category: high (H), medium (M), or low (L).

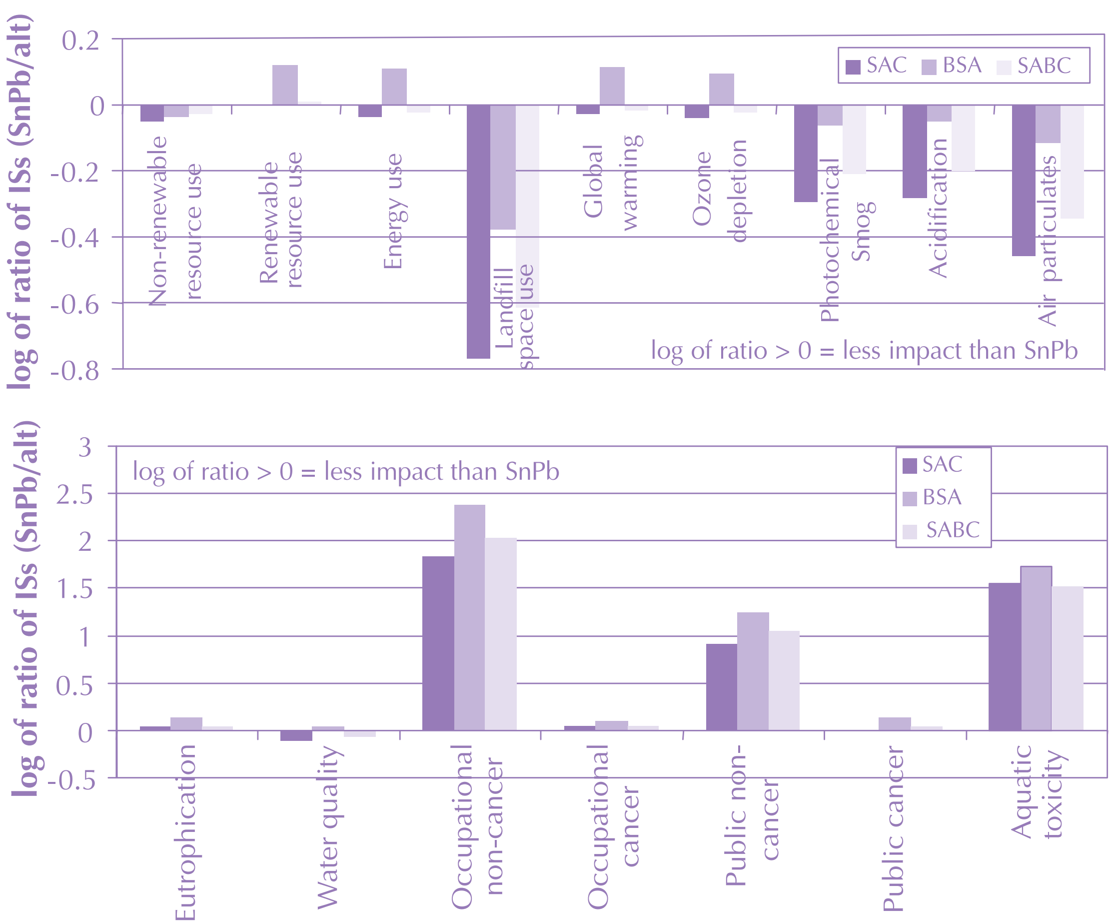
Note: Bold indicates the solder with the highest impact score within an impact category; shaded scores indicate the solder with the lowest impact score.

- Among the lead-free solders,
  - BSA has the lowest impact score in all categories except non-renewable resource use;
  - SAC has the highest impact score in all categories except aquatic ecotoxicity and occupational cancer; and
  - SABC has the highest impact score in occupational cancer and aquatic ecotoxicity, and the lowest impact score in non-renewable resource use.

Note that these impact scores only indicate the relative or incremental differences among the solders and do not necessarily indicate any particular level of concern.

Figure 4.1 displays the relative differences of the 16 environmental and human health impact categories presented in Table 4.1. The values derived for the figure are the log of the ratio of the alternative solder impact score to that of the SnPb baseline solder score for each impact category. Log ratios reported as a positive number reflect a favorable comparison (lesser relative impacts) to the baseline SnPb solder for the alternative; a negative number represents an unfavorable result (greater relative impacts) as compared to the baseline solder. Note that comparisons should only be made *within* not *across* impact categories.

Figure 4.1. Relative Comparison of Paste Solder Life-Cycle Impact Scores



Note: Do not compare across impact categories.

Which Life-Cycle Stages Drive the Impact Scores?

A summary of the top contributing life-cycle stages for each solder by impact category is presented in Table 4.2. The life-cycle stage or stages that contribute 50 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 50 percent are listed; the life-cycle stage with the greatest contribution is listed first. The use/application life-cycle stage dominates many of the solder impacts.

- For SnPb, the use/application stage contributes the majority of the impacts for thirteen out of sixteen impact categories. Nearly all of the impacts associated with the use/application stage result from the generation of the energy consumed during the solder reflow process during PWB assembly.
- SAC has nine impact categories where the use/application stage is a major contributor and six categories in which the upstream stage provides the majority of impacts. The upstream impacts are primarily from silver production. EOL and manufacturing are top contributors to the occupational non-cancer impact category only.
- The BSA impacts are driven by the use/application stage in eleven categories, by the upstream stage in three categories, and by EOL in two categories.
- The impact categories for SABC are driven by the same life-cycle stages as BSA with the exception of the occupational non-cancer impact category, which is driven by the EOL and manufacturing stages, as is the case for SnPb and SAC.

Table 4.2. Paste Solder Life-Cycle Stages Contributing a Majority to Each Life-Cycle Impact

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
Stratospheric ozone depletion	Use/application	Use/application	Use/application	Use/application
Photochemical smog	Use/application	Upstream	Use/application	Use/application
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

Natural Resource Impacts

Non-renewable resource use. Non-renewable natural resources are typically abiotic materials, such as mineral ore or fossil fuels. The use/application stage contributes 65 to 96 percent of the non-renewable natural resource use impact category depending on the solder. Electricity generation in the reflow application process is the main driver for this impact category. SnPb consumes the most electricity per functional unit due to its higher relative density (see Table 2.1). BSA consumes less energy during reflow application relative to the other paste solders, because of its lower melting temperature (despite its high density). SAC and SABC have greater overall impacts for this category due to the significant contribution of upstream silver production.

Renewable resource use. Renewable resources are typically biotic materials, such as forest or animal products, plants, and water. Impacts from the use/application stage contribute 93 to 99 percent of the total renewable resource use category and are due primarily to the consumption of water for electricity generation in the reflow application process. SnPb has the highest impact score in this category, because it consumes the most electricity per functional unit due to its higher relative density (see Table 2.1). BSA has the lowest impact category score, because it consumes less electricity during reflow application relative to the other paste solders due to its lower melting temperature (despite its high density).

Energy use. Energy use impact scores are the sum of electrical and fuel energy inputs. Electricity use in the reflow application process is the main driver for this impact category. SAC has the highest impact score due to the energy used during silver extraction and processing. The energy impacts from silver processing approach those of tin processing, even though the silver content (3.9%) of SAC is considerably less than the tin content (95.5%). BSA's energy use score is lower relative to the other paste solders because of its lower melting temperature (see Table 2.1).

Landfill space use. Landfill space use impacts are calculated based on the volume of landfill space consumed by solid, hazardous, and/or radioactive waste. SnPb has the lowest score for this impact category; SAC has the highest score. Silver production, specifically the generation of slag, is responsible for the upstream life-cycle stage dominating this impact category for the lead-free solders. For example, the upstream life-cycle stage accounts for 67 to 84 percent of the total landfill space impact score for the lead-free solders. In contrast, the upstream stage accounts for less than 1.4 percent of the total SnPb landfill space impact score, which is driven by the use/application stage.

Abiotic Ecosystem Impacts

Global warming. 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 global warming potential equivalency factor. Global warming impacts follow the trend observed for the energy use category (i.e., the use/application stage drives this impact category), which is expected given that electricity generation produces significant amounts of carbon dioxide, a global warming gas. BSA has a substantially lower score in this category because it has a lower melting temperature, which reduces its energy consumption during reflow application. SAC has the highest score in this category due to the higher global warming scores for upstream silver extraction and processing relative to the other metals.

Stratospheric ozone depletion. Ozone depletion impact scores are based on the identity and amount of ozone depleting chemicals that are released to air. SAC has the highest score for this impact category, whereas BSA's score is the lowest. The use/application phase dominates the impacts for all of the solders, although the upstream stage contributes a larger portion of the total impacts for the lead-free alternatives than for SnPb. Electricity consumption in the solder reflow process is entirely responsible for ozone depletion impacts in the use/application phase. Silver production is the top contributor to the upstream life-cycle stage for the non-lead alternatives. It should be noted that some of the materials in the ozone depletion inventory should have been phased out and might have been (the inventory is just dated). An alternate analysis that was performed with only the non-phased out ozone depleting chemicals in the inventory showed similar differences between the solders; however, the manufacturing stage now dominates for all of the solders.

Photochemical smog. Photochemical smog refers to the release of chemicals that may react with sunlight in the atmosphere to produce photochemical oxidants, such as tropospheric ozone. Upstream and use/application stages both contribute significantly to the photochemical smog impact category for the lead-free solders, whereas the use/application stage contributes nearly 93 percent of the SnPb smog impacts. The solder reflow application process is the only contributor to the use/application stage, whereas silver production is the main contributor to the upstream stage.

Acidification. Acidification impacts refer to the release of chemicals that may contribute to the formation of acid precipitation. SAC has the highest impact score for this category; SnPb has the lowest score. Approximately 93 percent of the SnPb life-cycle acidification impacts are driven by the use/application stage. The lead-free solder impacts are driven by both the upstream and use/application stages. Electricity generation is the largest contributor to the use/application phase, whereas silver production drives the upstream contribution. Sulfur dioxide and nitrogen oxides are the main contributors of the acidification impacts.

Air particulates. Air particulate impacts are based on the amount of particulate matter with an average aerodynamic diameter less than 10 micrometers (PM_{10}) that is released to the air. Total suspended particulates/dust was used if PM_{10} data were not available. SnPb has the lowest score for this impact category; SAC has the highest score. Approximately 79 percent of the life-cycle air particulate impact score for SnPb is driven by the use/application stage. Dusts generated during silver production and during electricity generation for reflow application drive the impact score for the lead-free alternatives.

Water eutrophication. Eutrophication (nutrient enrichment) impacts to water are based on the identity and concentrations of eutrophication chemicals released to surface water after treatment. The use/application phase accounts for 95 to 99 percent of total water eutrophication impacts for all of the paste solders. Chemical oxygen demand from the electricity generation process is responsible for most of these impacts. SnPb has the highest score for this impact category, although its score may be indistinguishable from those of SAC or SABC given uncertainties in the data. BSA has less of a water eutrophication impact than the other solders because it consumes less energy during solder application.

Water quality. Water quality impacts are characterized as surface water impacts due to the biological oxygen demand and total suspended solids in the wastewater streams released to surface water. SAC has the highest score for this impact category, and BSA has the lowest score. The use/application stage accounts for 95 percent of the water quality impacts for the SnPb solder and between 71 to 78 percent for the lead-free solders. Upstream production of the lead-free alternative solders contributes 18 to 26 percent of the water quality impacts, with silver production contributing a disproportionately large amount relative to the silver content in the solders.

Human Health and Ecotoxicity

Occupational health—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. Occupational non-cancer impacts for SnPb, SAC and SABC receive significant contributions from the solder manufacturing process. The toxicity of lead is very high relative to the other metals, which, when combined with lead's relatively high input amount, results in the lead-based occupational non-cancer impacts being far greater than those from the lead-free alternatives. SnPb impacts range from 69 to 239 times greater than the other solders. Silver drives the occupational non-cancer impacts for the lead-free solders because it has the highest non-cancer toxicity among the constituent metals of the non-lead alternatives. BSA has the lowest impact score for this impact category because it is comprised of the least amount of silver of the non-lead solders.

Occupational health—cancer. Natural gas used to generate electricity for reflow application is the greatest contributor to this impact category for all of the paste solders. SnPb has the greatest occupational cancer impact score, but it is not significantly higher than those for SABC and SAC. BSA has the lowest impact score, because less electricity is used to reflow BSA. The high impact score for natural gas is primarily due to the relatively large amount of natural gas inputs to the associated processes and not necessarily due to its carcinogenicity. When no cancer classification or measure of carcinogenicity has been given to a potentially toxic material, the LCA methodology assigns average default values to those materials. Thus, the occupational cancer results indicate that impacts are not driven by any classified (known or suspected) carcinogen.

Public human health—non-cancer. Impact scores are calculated based on the identity, inherent chronic toxicity, and amount of toxic chemical outputs to air, soil, and water. The public non-cancer impacts for SnPb are far greater than the other solders due to lead's high toxicity and its greater landfill leachability as determined by TCLP testing. SnPb impacts, which are driven by the end-of-life stage, range from eight to seventeen times greater than the lead-free solders. For the non-lead solders, the public non-cancer impacts are driven by sulfur dioxide emissions from upstream silver production. BSA has the lowest score for this impact category.

Public human health—cancer. Nitrogen oxides from electricity generation needed for reflow application are the greatest contributors to public cancer impacts for all of the solders. SAC has the highest score in this impact category due to the significant contribution from the upstream production of silver. BSA has the lowest score in this category because it has a lower melting temperature, which reduces its energy consumption during reflow application. Similar to occupational cancer impacts, results are driven by materials that have not been classified or measured as carcinogens, indicating little concern over any known carcinogens.

Aquatic ecotoxicity. Aquatic ecotoxicity impacts refer to the effects of chemical outputs on non-human living organisms. SnPb has the highest score for this impact category; BSA has the lowest score. The EOL stage accounts for 99.9 percent of the aquatic ecotoxicity impact category for SnPb, 70 percent for BSA, 65 percent for SABC, and 45 percent for SAC. The SnPb solder impacts are driven by lead emitted to water from landfills. The upstream life-cycle stage is the main contributor to aquatic toxicity for SAC, and it is a significant contributor for the other lead-free solders. Cadmium emitted to water from silver production is the driver.

Question 5:
How do the environmental and health impacts compare among bar solders?

This section compares the results for each impact category described in Question 3 for the bar solders. Table 5.1 presents the life-cycle impact scores for each of the bar solders evaluated and a quality rating given to each impact category score. Highlights from the results are as follows:

- Among all of the solders,
  - SnPb has the greatest impact category score (shown in bold) in four impact categories, all of which are toxicity-related;
  - SAC has the highest impact category score in the remaining twelve impact categories;
  - SnPb has the lowest impact category score (shaded values) among the solders in five impact categories; and
  - SnCu has the lowest scores in the remaining eleven categories.
- Among the lead-free solders,
  - SAC has the highest impact score in all sixteen of the categories evaluated.

Note that these impact scores only indicate the relative or incremental differences among the solders and do not necessarily indicate any level of concern.

Table 5.1. Bar Solder Life-Cycle Impact Scores

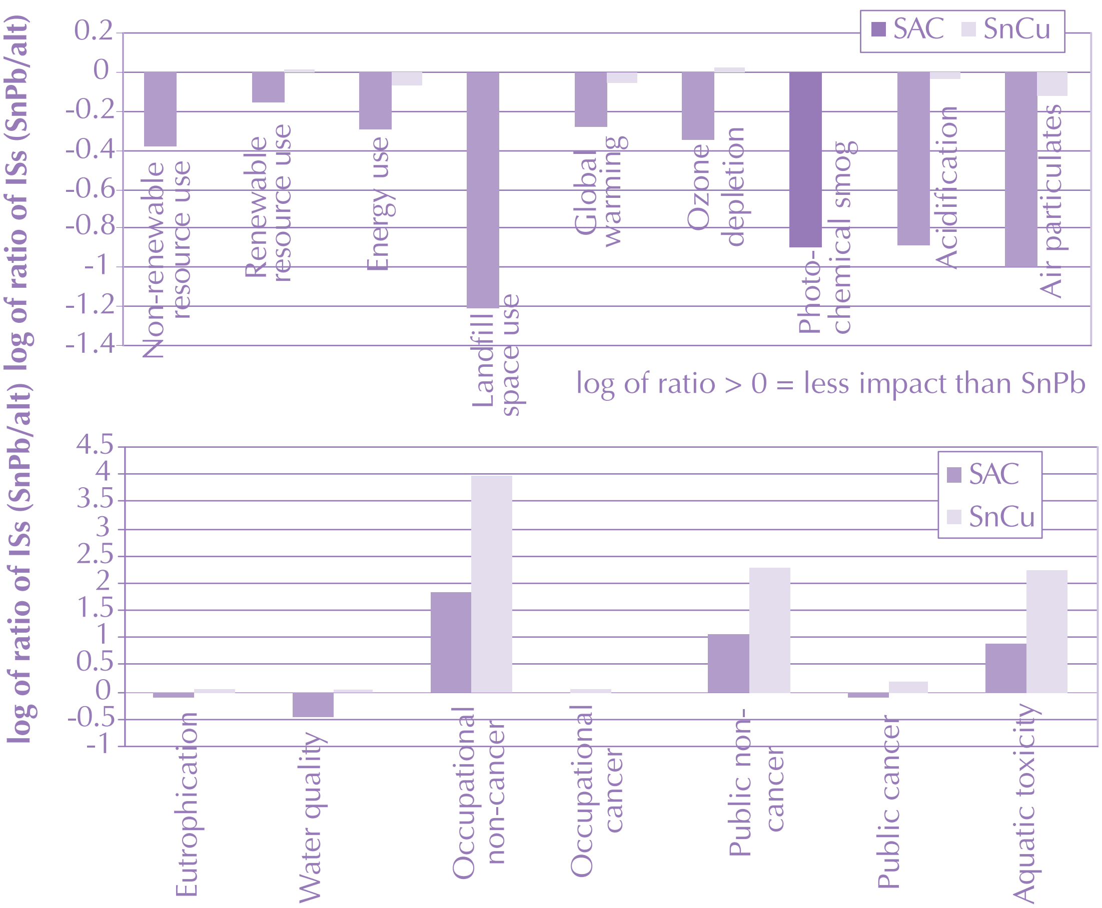
Impact category	Units per functional unit[a]	Quality rating[b]	SnPb	SAC	SnCu
Non-renewable resource use	kg	M-H	3.15E+02	**7.68E+02**	3.12E+02
Renewable resource use	kg	M-H	6.03E+03	**8.76E+03**	5.83E+03
Energy use	MJ	H	2.91E+03	**5.77E+03**	3.40E+03
Landfill space use	m^3	M-H	1.34E-03	**2.14E-02**	1.33E-03
Global warming	kg CO_2-equiv.	H	1.87E+02	**3.57E+02**	2.16E+02
Stratospheric 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
Air particulates	kg	M-H	1.49E-01	**1.47E+00**	1.99E-01
Water 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 health–non-cancer	kg noncancertox-equiv.	M-H	**7.15E+05**	1.09 E+04	6.53E+01
Occupational health–cancer	kg cancertox-equiv.	L-M	**5.94E+01**	5.75E+01	5.49E+01
Public human health–non-cancer	kg noncancertox-equiv.	M-H	**1.33E+05**	1.22E+04	7.26E+02
Public human health–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

[a]The functional unit is 1,000 cc of solder applied to a printed wiring board.
[b]Quality summarizes the overall relative data quality associated with each impact category: high (H), medium (M), or low (L).

Notes: Bold impact scores indicate the solder with the highest score for an impact category.
Shaded impact scores indicate the solder with the lowest score for an impact category.

Figure 5.1 displays the relative differences of the 16 environmental and human health impact categories presented in Table 5.1. The values derived for the figure are the log of the ratio of the alternative solder impact score to that of the SnPb baseline solder score for each impact category. Log ratios reported as a positive number reflect a favorable comparison (lesser relative impacts) to the baseline SnPb solder for the alternative. A negative number represents an unfavorable result (greater relative impacts) as compared to the baseline solder. Note that comparisons should only be made *within* not *across* impact categories.

Figure 5.1. Relative Comparison of Bar Solder Life-Cycle Impact Scores



Note: Do not compare across impact categories.

Which life-cycle stages drive the impact scores?

A summary of the top contributing life-cycle stages for each solder by impact category is presented in Table 5.2. The life-cycle stage or stages that contribute 50 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 50 percent are listed. The life-cycle stage with the greatest contribution is listed first. The use/application life-cycle stage dominates many of the impacts.

- For SnPb, eleven of the sixteen impact categories are driven by contributions from the use/application stage.

- SnCu has thirteen impact categories where the use/application stage is the major contributor.
- For SAC, the upstream life-cycle stage plays a more important role than it does for SnPb or SnCu. The upstream impacts are primarily from silver production. SAC has ten impact categories where the upstream stage is the main contributor. The use/application stage dominates four categories.
- The end-of-life stage drives the aquatic ecotoxicity impact category for all three solders.
- For all categories that are dominated by the use/application stage, except for occupational and public health categories, impacts result from the generation of electricity used in the wave application process.
- For the public and occupational health categories, inputs to the wave application process itself dominate the use/application stage.

Table 5.2. Bar Solder Life-Cycle Stages Contributing a Majority of Life-Cycle 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
Stratospheric ozone depletion	Use/application	Upstream	Use/application
Photochemical smog	Use/application	Upstream	Use/application
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/application, 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

Natural Resource Impacts

Non-renewable resource use. Non-renewable natural resources are typically abiotic materials, such as mineral ore or fossil fuels. The use/application stage dominates the impacts for SnPb and SnCu, whereas the upstream stage contributes 66 percent of the non-renewable resource impacts for SAC. An interesting note is that the use/application stage scores are nearly the same for all three solders. However, silver production contributes significantly to the upstream impacts for SAC, despite the fact that silver comprises only 3.9 percent of the overall solder content of SAC. These upstream impacts cause SAC to have a greater impact score than SnPb or SnCu.

Renewable resource use. Renewable resources are typically biotic materials, such as forest or animal products, plants, and water. Impacts from the generation of electricity in the use/application stage dominate impacts for all three solders, contributing 63 to 94 percent of the total impacts. The upstream stage is an important contributor to the overall SAC impact score, resulting in a greater total impact score for SAC compared to SnPb and SnCu.

Energy use. Energy use impact scores are the sum of electrical and fuel energy inputs. The materials extraction and processing (upstream) life-cycle stage drives the SAC results for this impact category and causes it to dominate the other two solders. SnPb and SnCu are driven by the use/application stage for this impact category, which is driven entirely by electricity consumption in the bar solder process. Energy impacts from silver processing are greater than impacts from tin processing, even though the silver content (3.9%) of the SAC solder is much less than that of tin (95.5%). This illustrates the relatively high energy intensity of silver extraction and processing compared to the other solder metals.

Landfill space use. Landfill space use impacts are calculated based on the volume of landfill space consumed by solid, hazardous, and/or radioactive waste. Impacts for SAC are 16 times greater than those for SnPb and SnCu. Landfill space use for SAC is driven by the upstream life-cycle stage, which alone exceeds the total impacts from SnPb and SnCu. Upstream silver production, specifically the generation of slag, contributes 87 percent of the total life-cycle landfill space use for SAC. The end-of-life stage is the leading contributor to the total impacts for SnPb and SnCu.

Abiotic Ecosystem Impacts

Global warming. 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 global warming potential equivalency factor. Global warming impacts follow the trend observed for the energy use category (i.e., SAC is driven by the upstream stage, SnPb and SnCu are driven by the use/application stage) due to the large amounts of electrical energy used over the life-cycle of these solders. Electricity generation produces considerable amounts of carbon dioxide, a global warming gas. Unlike the paste solders where the global warming impacts are dominated by the use/application stage, both the upstream and use/application stages contribute significantly to the global warming impacts for each of the bar solders. This is because the reflow process uses more energy than the wave process and thus dominates the impacts for paste solder.

Stratospheric ozone depletion. Ozone depletion impact scores are based on the identity and amount of ozone depleting chemicals that are released to air. SAC has more than twice the ozone depletion impact score of the other bar solders. The use/application stage dominates for SnPb (82%) and SnCu (87%); however, despite SAC's nearly equivalent impact score for use/application, the upstream stage contributes 59 percent of the ozone depletion impact score for SAC. Electricity generation for the solder wave process is entirely responsible for the use/application stage impacts. Emissions from the extraction and processing of the metals, mainly silver, drives the upstream impacts. It should be noted that some of the materials in the ozone depletion inventory should have been phased out and maybe have been (the inventory is just dated). An alternate analysis that was performed with only the non-phased out ozone depleting chemicals in the inventory showed similar differences between the solders; however, the manufacturing stage now dominates for all of the solders.

Photochemical smog. Photochemical smog refers to the release of chemicals that may react with sunlight in the atmosphere to produce photochemical oxidants, such as tropospheric ozone. SAC has the highest score for this impact category; SnPb has the lowest score. Nearly 91 percent of the SAC photochemical smog impacts are driven by the upstream stage, whereas SnPb and SnCu are driven by the use/application stage. Air emissions from silver production account for 87 percent of the total smog impact for SAC. Air emissions from electricity generation for the solder wave process are the only contributors to the use/application stage impacts.

Acidification. Acidification impacts refer to the release of chemicals that may contribute to the formation of acid precipitation. SAC has the highest acidification impact score, with the upstream stage accounting for nearly 91 percent of the score. The use/application stage scores are approximately equal for each solder. However, this stage contributes a majority of the total SnPb and SnCu impacts due to the much lower impacts from the upstream stage. Electricity generation is the largest contributor to the use/application phase, whereas silver production drives the upstream contribution. Sulfur dioxide and nitrogen oxides are the main contributors of the acidification impacts for all of the solders.

Air particulates. Air particulate impacts are based on the amount of particulate matter with an average aerodynamic diameter less than 10 micrometers (PM_{10}) that is released to the air. Total suspended particulates/dust was used if PM_{10} data were not available. The upstream stage drives the air particulate impact category for all of the solders due to dusts generated during upstream metals production. The total impact category score is significantly higher for SAC due to dusts generated during silver production, which accounts for 84 percent of the total impact category score. Dusts from electricity generation for wave application contribute 38 percent and 29 percent of the impacts for SnPb and SnCu, respectively.

Water eutrophication. Eutrophication (nutrient enrichment) impacts to water are based on the identity and concentrations of eutrophication chemicals released to surface water after treatment. SAC has the highest score in this impact category, and SnCu has the lowest. The use/application phase accounts for at least 75 percent of the total water eutrophication impacts for each of the bar solders. Upstream process impacts, primarily silver production, account for 23 percent of the overall impacts for SAC, but the upstream stage contributes less than 1 percent of the total impact scores for SnCu and SnPb. Flows of chemical oxygen demand from the electricity generation process for all of the solders and from silver production for SAC are responsible for most of these water eutrophication impacts.

Water quality. Water quality impacts are characterized as surface water impacts due to the biological oxygen demand and total suspended solids in the wastewater streams released to surface water. SnCu has the lowest score for this impact category; SAC has the highest impact score. The upstream stage contributes a significant portion of the total water quality impacts for SAC. SnCu and SnPb water quality impacts are driven by the use/application phase. Silver production is again the primary contributor to the upstream impacts, whereas electricity generation for bar solder application drives the use/application stage impacts.

Human Health and Ecotoxicity

Occupational health—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. The occupational non-cancer score for SnPb is far greater than the score for the other solders because of SnPb's higher inherent toxicity compared to the other solders. The manufacturing, use/application, and EOL life-cycle stages largely contribute to the total impacts, regardless of the solder type. Bar solder inputs to the wave application process are the top contributors to the use/application stage for all of the solders.

Occupational health—cancer. SnPb has the greatest occupational cancer impact score, but its score is not significantly higher than those for SnCu and SAC. All four life-cycle stages contribute to the occupational cancer scores. The use/application stage is the greatest contributor to the total. The top three 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 three contributors are natural gas from tin production, bar solder from wave application, and tin from bar manufacturing. The high impact score for natural gas is primarily due to the relatively large amount of natural gas inputs to the associated processes and not necessarily due to its carcinogenicity. When no cancer classification or measure of carcinogenicity has been given to a potentially toxic material, the LCA methodology assigns average default values to those materials. Thus, the occupational cancer results indicate that impacts are not driven by any classified (known or suspected) carcinogen.

Public human health—non-cancer. Impact scores are calculated based on the identity and amount of toxic chemical outputs with dispositions to air, soil, and water. Inventory items do not truly represent long-term exposure. Instead, impacts are relative toxicity weightings of the inventory. The public non-cancer impacts for SnPb are far greater than the other solders due to lead's high hazard value and its greater landfill leachability as determined by TCLP testing. The EOL stage contributes 99.5 percent of the total SnPb public non-cancer impacts. SAC is driven largely by sulfur dioxide emissions (50%) and lead emissions to soil (37%) from silver production in the upstream stage. SnCu is driven by sulfur dioxide emissions from the generation of electricity in the use/application stage (62%).

Public human health—cancer. SAC has the highest public cancer impact score of the three solders. Wave soldering during the use/application life-cycle stage dominates the impacts for all three solders, whereas the upstream stage is a significant contributor to the total impact for SAC. Flux material released during wave soldering is the top contributor to the use/application impact score. Potential upstream impacts arise from outputs of potentially carcinogenic materials in the extraction and processing of the various metals present in the solders. Potential cancer impacts from silver extraction and processing are disproportionately high compared to the percentage of metals in the solders.

Aquatic ecotoxicity. Aquatic ecotoxicity impacts refer to the effects of chemical outputs on non-human living organisms. The EOL stage accounts for 99.96 percent of the aquatic ecotoxicity impact category for SnPb, 96.4 percent for SnCu, and 86 percent for SAC, although the absolute aquatic ecotoxicity impact score is far greater for SnPb than for the other bar solders. For SAC, the upstream life-cycle stage contributes 14 percent to the total impacts; cadmium emitted to water from silver production is the driver. Landfilling is the largest contributor to the EOL impact for SnPb. Unregulated recycling and disposal is the greatest process group contributor to EOL impacts for the lead-free solders.

Question 6:
What are the limitations of the study?

This section summarizes the main limitations and data uncertainties in the study's methodology. It also presents the results of additional analyses that were performed for the reflow energy consumption, silver mining and processing data set, and leachate data. These analyses were performed because they evaluated data with the largest uncertainty or because the data were major contributors to the inventory results.

LCA limitations and data uncertainties

Uncertainties exist in the life-cycle inventory (LCI) and life-cycle impact assessment (LCIA). Uncertainty in the inventory data for the LFSP life-cycle assessment (LCA) includes, but is 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.

Uncertainties related to the impact assessment include, but are not limited to, the following:

- missing chemical equivalency or toxicity data; and
- model uncertainty/screening level analysis.

Additional reflow energy data analysis

Energy consumed during the use/application life-cycle stage constituted a majority of the impacts for many of the impact categories evaluated. Electricity consumption data for the paste solder application process are based on primary data (considered to be of good quality) collected from two facilities where test runs were conducted. The two ovens in which these tests were performed represent a large range in energy consumption 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 to determine the life-cycle impacts. The additional analysis determined the sensitivity of these results to the energy consumption rate using both the high and low data points from the testing. The energy use impact category was selected as an example of the potential sensitivity to the electricity consumption data, because a large percentage (between about 82 and 91 percent) of the baseline impacts in this category for all four solders resulted from the energy consumed during reflow.

Figure 6.1 shows the results of the reflow application energy additional analysis for all three scenarios (low energy, baseline, and high energy). Although the magnitude of the scores changed, the relative comparison among the solders did not: SAC still has the highest impacts, followed by SABC, then SnPb, and finally BSA. As illustrated in Table 6.1, the use/application phase still drives the energy use impact category. This suggests that the results are not too sensitive to the uncertainties in the reflow application energy estimates (assuming the range used in this sensitivity analysis represents a true or realistic range of the energy estimates for a reflow application process).

Figure 6.1. Reflow Application Energy Additional Analysis

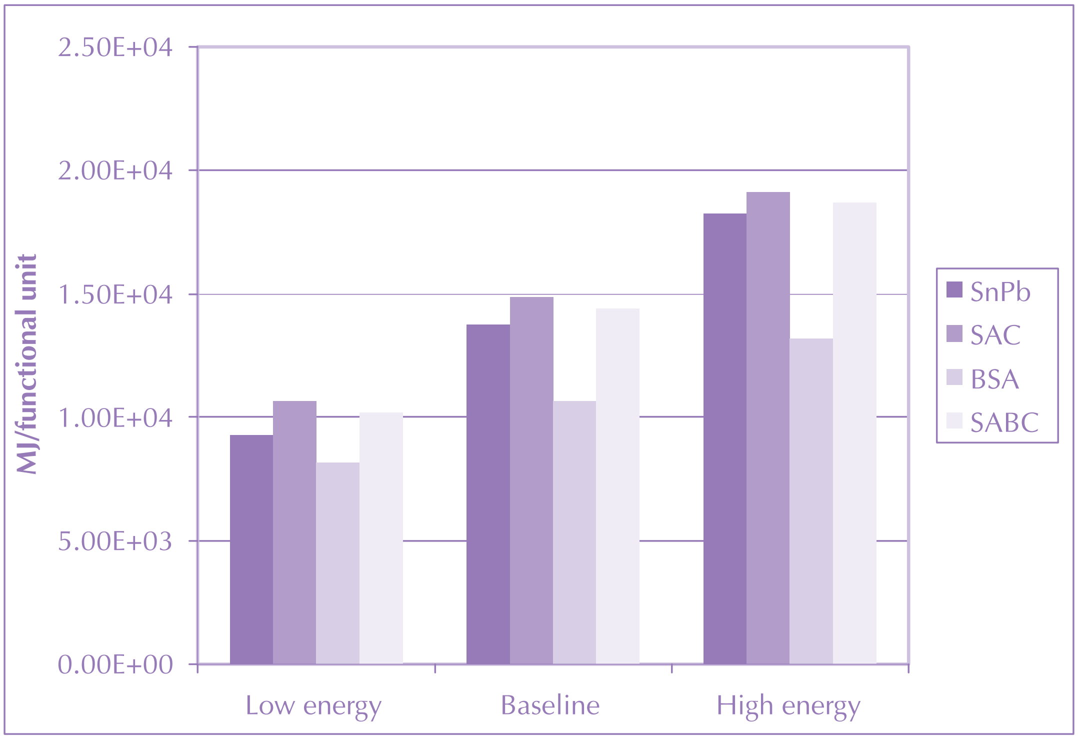


Table 6.1. Percent Contribution of Use/Application Stage to Energy Impacts

Energy estimate	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%

An additional energy analysis was not performed for the wave application process, because: (1) the energy data that were used are expected to be representative of general wave applications, even though they are only from one data set; and (2) the relative magnitude of the energy from use/application compared to the other life-cycle stages was lower for wave applications than for reflow applications.

Additional silver inventory analysis

Due to the large influence that silver production had on many of the impact categories of the lead-free solder pastes, an additional analysis was performed by substituting a publicly available silver data set for the one used in the LFSP (i.e., GaBi). Although the quality of this alternate data set could not be verified, and thus it was not used for the LFSP baseline analysis, it is used here to demonstrate the impacts of using another data set on the overall results. Table 6.2 compares the results of the additional analysis to the baseline results for paste solder. For the paste solders, the alternate 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, despite 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 alternate silver inventory that have lower values than the associated flows in GaBi. Due to a lack of available documentation for the alternate 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 6.2. Comparison of Paste Solder Baseline and Additional LCA Analyses

Solder	Baseline (GaBi data set)[a]		Alternate (DEAM data set)[a]	
	Highest score[b]	Lowest score[b]	Highest score[b]	Lowest score[b]
SnPb	6	5	14	0
SAC	10	0	1	1
BSA	0	11	1	15
SABC	0	0	0	0

[a]Numbers indicate the number of impact categories where solder has the highest or lowest score.

[b]GaBi: Software system for Life Cycle Engineering, PE & IKP, 2000; DEAM: Database for Environmental Analysis and Management, Ecobilan, 1999.

As shown in Table 6.3, the additional analysis for bar solders also results in an overall decrease in importance of the silver mining process. The number of categories for which SnPb has the highest relative impact score rises from four to nine, whereas 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.

Table 6.3. Comparison of Bar Solder Baseline and Additional LCA Analyses

Solder	Baseline (GaBi data set)		Alternate (DEAM data set)	
	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.

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 alternate data set were inconclusive; therefore, the GaBi data set was chosen for the LFSP baseline analysis. However, these results show the possible variability and sensitivity of the results to the silver inventory data and suggest that additional effort to increase the quality of the silver mining and extraction data would be well spent.

Additional leachate data analysis

The leachability study conducted for the LFSP project was used to estimate the outputs of metals from landfilling printed wiring board (PWB) waste or residual metals in incinerator ash. Lead was found to leach to a much greater extent than the other metals in the solders being analyzed in this study. This leachability contributed to the large public non-cancer and aquatic ecotoxicity impacts for the SnPb solder as compared to the other solders for both the paste and the bar solder results. The Toxicity Characteristic Leaching Procedure (TCLP) used for the LFSP study is based on a standard EPA TCLP test protocol using acetic acid, a substance known to readily leach lead. However, it is unknown to what extent these test conditions represent actual landfill conditions, which can vary dramatically over the lifetime of a landfill. The additional analysis, therefore, was conducted using the detection limit of lead during the leachability testing as a lower bound of lead leachability 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 amount leached is equivalent to the study detection limit for the leachability of lead), the SnPb solder impact scores are still at least 2.5 times higher than the score of the next closest solder for public non-cancer impacts, and a full order of magnitude higher for aquatic toxicity. However, the relative differences between SnPb and the lead-free solders 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 solder would still have higher potential impacts for both public non-cancer and aquatic toxicity than the other solders, based primarily on its relative toxicity.

Question 7:
What can electronics manufacturers do to reduce environmental and health impacts?

This section identifies selected opportunities for reducing the overall environmental and human health impacts of solder used in electronics manufacturing based on the results of the LCA. Improvements in the upstream and use/application stages are presented and analyzed due to the significant impacts resulting from these stages and their associated potential for improvement. Though not specifically detailed here, additional opportunities for improvement may exist in other areas of the solder life cycle.

Areas of Opportunity for Human Health and Environmental Impact Reductions

Upstream and Solder Manufacturing. Upstream processes result in significant contributions to the environmental and human health impacts for solder, particularly the lead-free alternatives containing silver. Table 7.1 presents impact categories in which at least 30 percent of the overall impact score resulted from upstream processes. The overall percentage contribution in each category is presented for each solder type. As shown in the table, flows from upstream materials extraction and processing made significant contributions in a total of seven different categories for paste solders and in as many as eleven impact categories for bar solders, depending on the solder.

Table 7.1. Percentage Contribution of Upstream Processes to Overall Impacts by Category

Impact categories*	Paste solders				Bar solders		
	SnPb	SAC	BSA	SABC	SnPb	SAC	SnCu
Non-renewable resource use	–	–	33	–	–	66	–
Energy use	–	–	–	–	–	66	38
Landfill space use	–	83	65	76	–	94	–
Global warming	–	–	–	–	31	65	41
Stratospheric ozone depletion	–	–	–	–	–	59	–
Photochemical smog	–	52	38	41	–	91	–
Acidification	–	54	39	40	–	91	33
Air particulates	–	74	54	66	58	96	69
Water quality	–	–	–	–	–	73	–
Public human health–non-cancer	–	74	58	65	–	95	31
Aquatic ecotoxicity	–	51	–	31	–	–	–

[1]As an indication of significance, table includes only categories for which the contribution from upstream processes to the overall impact score exceeds 30 percent for at least one solder.
'—' indicates the contribution made by upstream processes does not exceed 30 percent of the overall impacts in the category.

Virgin materials extracted and refined during upstream processes are often combined with recycled metal during the manufacture of solder. The percentage of the solder comprised of virgin material can vary widely by solder type and solder manufacturer. Table 7.2 lists the average virgin material content of each of the solders evaluated, along with the range of data as reported by the manufacturers for this study.

Table 7.2. Average Virgin Content of Base Metals Used in Solder Manufacturing

Metal	SnPb	SAC	BSA	SABC	SnCu	Range[1]
Sn	68%	74%	74%	74%	74%	20-100%
Pb	68%	–	–	–	–	20-100%
Ag	–	68%	68%	68%	–	0-100%
Cu	–	93%	–	68%	81%	20-100%
Bi	–	–	99%	99%	–	99%

[1]Range of virgin content used across solder types as reported by solder manufacturers.

Composition of the solders ranged from no recycled content to 80 percent of the composition of some solder alloys for Sn and Pb, and as high as 100 percent recycled content for silver, depending on the solder manufacturer and the alloy. Because the recovery process is prohibitively expensive, bismuth is not currently being reclaimed by the electronics industry. Therefore, Bi is composed of nearly entirely virgin material. Manufacturers producing both paste and bar solders of a particular alloy reported no difference in virgin material content between the solder types for the alloy.

Post-consumer recycling reclaims scrap metal from electronic products that enter the waste stream at their end-of-life, refining the metallic content to its base metals. By contrast, post-industrial recycling processes are operated by solder manufacturers to accept and reclaim in-process manufacturing wastes from the manufacture or use/application of solder during the PWB assembly process. Because the process wastes are mostly waste solder compounds, the metals need only to be refined to common alloys rather than to base metals. Use of secondary metals reclaimed through post-industrial recycling, therefore, are preferable to those derived from post-consumer scrap due to the energy efficiency of the reclamation process.

Given the importance of the upstream processes in many of the life-cycle impact categories, and the high percentage of virgin material used to manufacture the solders, an opportunity exists to reduce these impacts through the use of recycled metal. Reclaimed metal derived from either post-industrial or post-consumer recycling produces less environmental impact per volume than does the mining and extraction of virgin metal. Substituting recycled metals for virgin content will reduce the overall environmental footprint of the solder life cycle in several categories. For example, implementing a 25 percent reduction of virgin materials used in SAC solder paste results in a corresponding decrease of the overall impacts to air particulates, landfill space use, photochemical smog, and acidification of at least 22 percent. Similar, though less dramatic, reductions in the overall environmental footprint would occur in other categories listed in Table 7.1.

Use/Application of Solder Paste. The generation of energy required for the application of paste and bar solders results in the largest contribution to the overall impact score for many of the impact categories, regardless of the solder type. Table 7.3 displays the percentage of the impacts attributable to use/application processes for each impact category for which the use/application stage made the largest contribution. As shown in the table, the use/application stage was the top contributor to as many as fourteen separate impact categories for paste solders. Impacts from the use/application stage were equally dominant for bar solder.

Table 7.3. Percentage Contribution of Use/Application Processes by Impact Category

Impact categories	Paste solders			
	SnPb	SAC	BSA	SABC
Non-renewable resource use	77	64	52	68
Renewable resource use	89	84	86	86
Energy use	91	79	86	82
Landfill space use	65	–	–	–
Global warming	88	77	83	80
Stratospheric ozone depletion	39	33	36	35
Photochemical smog	65	–	42	38
Acidification	65	–	43	39
Air particulates	79	–	45	–
Water eutrophication	97	94	96	95
Water quality	87	65	70	71
Occupational health–non-cancer	31	–	–	–
Occupational health–cancer	43	43	38	43
Public human health–non-cancer	–	–	41	34
Public human health–cancer	33	30	32	33
Aquatic ecotoxicity	–	–	–	–

'—' indicates an impact category where the largest contributions resulted from a life-cycle stage other than use/application.

After being applied to the PWB, solder paste must be heated to a temperature high enough to melt, or reflow, the solder. The majority of impacts shown in the above table directly result from the production of the large amounts of energy required to heat the solder during the reflow process. Energy consumption can vary widely depending on the solder type and the equipment specifications and process operating parameters employed by the facility (see Question 8 for more details). Table 7.4 presents the energy consumption data collected during reflow solder testing conducted at two separate facilities in support of this project. To facilitate comparison of the results, testing was conducted using an identical protocol and under controlled conditions.

Table 7.4. Power Consumption During Reflow Testing

Solder type	Intel (kW)	Vitronics-Soltec (kW)	Power reduction
SnPb	23.3	8.3	–65%
SAC	25.2	9.1	–64%
BSA	15.7	6.8	–57%
SABC	25.2	9.1	–64%

As shown in the table, power consumption for the reflow solder process varied significantly across facilities, despite the use of similar test protocols. Energy consumption at the Intel facility was at a minimum 2.3 times greater than the energy consumed at Vitronics-Soltec for each solder evaluated. Reflow equipment designed for the high temperatures associated with lead-free, such as the oven at Vitronics-Soltec, are developed using the latest technologies and are optimized to achieve greater temperature stability through increased thermal efficiency. Given the importance of the use/application stage and the relative thermal inefficiency of assembly equipment optimized for SnPb, an opportunity exists to reduce the amount of energy consumed during lead-free assembly through equipment changes and process optimization. As shown in Table 7.4, power consumption can be reduced significantly by replacing older, less efficient reflow assembly equipment, or by optimizing current equipment to perform at the elevated temperatures required for lead-free soldering. For example, using the data in Table 7.4 for SnPb, a facility realizing a 65 percent reduction in power consumption through the replacement of equipment or by other means would result in reductions in potential environmental impacts ranging from 40-60 percent in most categories, as well as a 20 percent or greater reduction in occupational and public human health impacts. Though not presented in detail here, similar though less dramatic improvements would result from a reduction in energy consumption associated with the wave soldering process.

Question 8:
What are the challenges to implementing lead-free soldering?

There is no drop-in replacement for SnPb solder. The switch to lead-free solders affects many aspects of the manufacturing and assembly process, all of which must be considered by manufacturers seeking to effectively implement lead-free solder. The electronics industry and its suppliers have been working to develop the materials and techniques required for the successful implementation of lead-free solders during the manufacture of electronic devices. This section presents information developed or recorded during the performance of the LCA that can aid in the implementation of lead-free solder by industry. Even though there are many barriers and subtleties to implementation of an entirely new metallurgy, this section summarizes the current industry wisdom regarding key challenges to adopting lead-free solders.

Components. Identifying and securing lead-free components can be the most time-consuming and important aspect of lead-free soldering. Components used for SnPb are not capable of withstanding the elevated temperatures of lead-free assembly. Components manufactured with Sn or with NiPdAu finishes have successfully been developed for use with lead-free solders. Components that are certified for lead-free use conform to the RoHS standard of less than 0.1% Pb content. Components, however, must also be able to withstand 260°C peak temperatures associated with lead-free assembly. Particularly susceptible are plastic components such as connectors, LEDs, and capacitors. Many types of components rated for use in 255-260°C are currently being offered and certified for lead-free solder assembly (Lange et al., 2004).

Laminates. The higher temperatures needed for lead-free soldering place additional stress on the circuit board laminate, especially when performing multiple soldering operations. Some commonly used laminates, such as FR-4, may not be able to withstand the 260°C peak temperatures possible during lead-free assembly without charring or significant warping. Testing has indicated that key parameters to consider when choosing a laminate include the glass transition temperature (Tg), the decomposition temperature (Td), and the material coefficient of thermal expansion (CTE) (McGrath, 2005).

New high reliability laminates are being introduced for lead-free soldering. These laminates can be processed in a similar manner to "standard" laminate, but are able to withstand higher process temperatures and are better suited for use in situations where the end product may operate at higher temperatures or may be subject to thermal cycling. The higher temperature laminates can be more expensive than typical FR-4, but may be required depending on the assembly requirements.

Cleaning. Cleaning of flux residues from surfaces of process work takes on additional importance to remove more aggressive flux residues from circuitry. Lead-free flux formulations require higher flux capacity, higher oxygen barrier capability, and increased thermal stability to withstand the elevated process temperatures. Cleaning lead-free flux residues remaining on the surface becomes more challenging due to increased residue activity from flux-induced metallurgical reactions and more insoluble tin-salt formation. Cleaning takes on additional importance when pure tin components or tin surface finishes are used, as these lead to tin whisker formation that may create electrical shorting if not removed during cleaning.

Some combination of increased cleaning time, higher temperature cleaning, increased mechanical energy, or inclusion of a cleaning additive will likely be required to meet the increased cleaning requirements of lead-free soldering. The correct combination of factors depends greatly on process characteristics such as flux type, wave or reflow temperature, and the amount of non-soluble surface materials (e.g., solder balls) present. Although more difficult, cleaning of residues from lead-free assembly surfaces should be possible using existing SnPb process cleaning equipment.

Wave Soldering

Wave soldering will require solder pot temperatures in the range of 260-275°C depending on the solder. Under these conditions, a longer preheat will be needed to keep thermal shock to the board below 100°C, and to prevent damage to components. Other considerations specific to implementation of lead-free wave soldering are discussed below.

Equipment maintenance. Tin in high concentrations and at elevated temperatures has proven to be corrosive to many metals, including stainless steel. Leading lead-free solders (e.g., SAC) are comprised of a higher percentage of Sn than is SnPb. These high Sn solders have melting points at least 30°C higher than SnPb on average. At these elevated temperatures, the lead-free solders have been observed to be corrosive to process equipment used to both manufacture and apply the lead-free solders to PWBs (Sweatman et al., 2004; Morris and O'Keefe, 2003).

During the smelting and refining of the metals, solder manufacturers and post-industrial recyclers have observed more rapid corrosion of pumps, nozzles, and refining pots resulting in shortened equipment life (Cookson, 2002). In some cases, equipment that typically lasted seven years needed replacing in as little as two years. Erosion of stainless steel parts of wave soldering equipment including solder pot and pot fittings has been observed in wave soldering processes using high tin, lead-free solders. Corrosion of solder pots constructed of stainless steel can lead to failure in as little as 6 months (Morris, 2003). This phenomenon can pose a serious worker safety concern and increase substantially the industry costs of converting to lead-free solder.

Several potential solutions are being assessed and implemented by equipment manufacturers. The use of a small addition of nickel to stabilize wave soldering baths has been shown to inhibit corrosion in industry testing (Sweatman, 2004). Coatings, such as Melonite, have also been shown to slow the rate of corrosion, extending the life of the equipment. However, the coatings typically break down after time, leading eventually to the corrosion of the solder pot. Cast iron pots have been used by some equipment manufacturers to good effect, but can lead to the eventual leaching of iron that will contaminate the solder requiring more frequent bath dumps.

Solder bath maintenance. The higher temperatures of lead-free solder can lead to shortened bath life through the increased corrosivity of the high Sn-content solders. Increased erosion of copper from PWB circuitry has been observed during wave soldering leading to faster copper build-up in SAC and SnCu. The dissolution of copper in lead-free solders is nearly 3x as that in SnPb requiring frequent dilution or replacement with fresh solder (Aim, 2001). Iron leached into the bath as a result of Sn corrosivity must also be monitored (Barbini, 2005). Bath maintenance must be performed more frequently to prevent the buildup of harmful contaminants that adversely affect product reliability.

Solder dross. Higher dross rates from the formation of oxides at higher temperatures place an emphasis on solder pot control and maintenance. Dross consists of oxides formed at the surface of the molten solder through interaction with air. Due in part to higher pot temperature, dross formation rates for SnCu and SAC are roughly 2.5 times the rate for SnPb (Hwang et al., 2004). To minimize the formation of dross, the solder wave should be kept in standby mode or shut off when not actively passing work over the wave to reduce turbulence. Addition of solder dross inhibitors, such as phosphorus, can be effective inhibitors of dross formation, though phosphorus has been known to increase Sn corrosivity of copper [Sprovieri, 2004]. Higher dross rates may make the use of solder skimming or purifying equipment desirable, but care should be taken to not use the equipment on both SnPb and Pb-free solders to prevent lead contamination of the dross, which would preclude recycling.

Rework/Repair. Rework and repair conducted with lead-free solders differs from typical SnPb procedures because the alloys do not wet to the surface or wick into the holes as easily as does SnPb. Despite these differences, successful rework methods have been developed with lead-free solders for most types of components using a variety of tools and methods, both semi-automatic and by hand. Rework equipment used for SnPb can be used for rework of the lead-free solder with some minor modifications. The greatest problems arise from the different CTEs of the laminate, solder, and the underlying circuitry. The 30^{o}C higher temperatures required to rework lead-free connections place thermal stress on the materials that expand at different rates, potentially causing failure of the solder joint. Undergoing an additional thermal cycle may also damage components already stressed from the higher temperatures. Rework should also be performed using a solder that is metallurgically compatible with the original solder to prevent future solder joint reliability issues.

Reflow Soldering

The greatest challenges to implementation of lead-free solder technology during reflow arise from the tightened process control window and the ability of the equipment and materials to meet that window. The process window, which is defined at the lower end by the melting temperature of the alloy, and at the upper end by the maximum component temperature, drops from roughly 30^{o}C for SnPb solders to less than 20^{o}C for SAC. Complicated assemblies with high component densities exacerbate the problems related to a narrow process window. Considerations specific to the implementation of lead-free reflow soldering are presented below.

Paste Application. Solder paste is typically applied by a screen printing process. A paste is first applied to the stencil, filling the stencil apertures, and then applied to the PWB using a squeegee or enclosed print head. The release characteristics of SnPb solder paste are well known. Lead-free solder paste, however, has a higher viscosity than SnPb solder, due to its higher metal content, and has a tendency to stick to the aperture walls (Ashmore, 2005). Lead-free solder paste also exhibits lower wetting ability than SnPb solder, placing an emphasis on printing accuracy not needed with SnPb solder, which tends to self-correct during reflow.

Research has indicated that stencil material, manufacturing, and screen printing techniques all have to be examined when implementing lead-free solder. Nickel-based stencils have displayed good release and accuracy characteristics under testing (Ashmore, 2005). Manufacture of stencils from the same material using different techniques displayed varying results, indicating that lead-free solder may be sensitive to the techniques used. Finally, adjustment in the rate and pressure of squeegee application of the solder may have to be adjusted to account for the differing characteristics of lead-free solder pastes.

Reflow Profiles. Reflow profiles define the time/temperature relationship required to promote the formation of reliable solder joints on a PWB assembly. Key profile parameters include time above preheat, time above liquidous (TAL), peak temperature, preheat and cooling zone ramp rates, and overall cycle-time. Optimization of the profile involves the use of thermocouples to measure surface and component temperatures at key locations to determine if the temperatures fall within the process control window. A successful profile will minimize the temperature differentials (DT) for the assembly. A large DT indicates that areas of the assembly may have been heated excessively while other areas may be insufficiently heated, resulting in a variety of solder defects such as non-wetting, voiding, or damaged devices.

Profiles are product-specific, solder/flux-specific, and are largely dependent upon the capabilities of the reflow equipment making it difficult to develop a standard profile for lead-free soldering. Lead-free solder profiles, however, are typically characterized by longer soak times during preheat and by higher peak temperatures than the profiles for SnPb assembly. The longer soak times are required to bring both the board and the components to equilibrium prior to reaching the reflow temperature to limit thermal shock and improper joint formation.

Profiles exhibiting the best performance for lead-free soldering are either the ramp-soak-spike (RSS) or the ramp-to-spike (RTS) form. Solder pastes utilizing water-based fluxes should not be used with RSS profiles because the longer soak times may break down the flux prior to reflow. RTS profiles have a shorter cycle-time and have been demonstrated to perform well with lead-free solders. If, however, a large DT exists or if you have older reflow equipment, a RSS profile may be a more appropriate choice.

Reflow Ovens. Although existing reflow equipment is able to provide the 250-260°C heating environments required to process lead-free assemblies, the ability of the oven to maintain the process within the tighter process window should be investigated. Thermal efficiency in older equipment was often sacrificed in favor of shorter response times to the varying demands of multiple reflow profiles in the production environment. Many older-style ovens were prone to heating different parts of an assembly at varying rates, often depending upon the color and texture of the parts and substrates being reflowed. As a result, older equipment may lack the ability to maintain the proper amount of control over the oven environment needed to minimize DT on the product, and may have to be modified or replaced.

Ovens developed to meet the challenges of lead-free soldering typically use forced convection heating. By circulating warm air around the assemblies, heat is provided in a uniform and controlled manner that minimizes DT. Testing confirmed that these ovens are more thermally efficient, consuming nearly a third of the power consumed by older ovens (see Table 7.4). In addition, the maximum temperature and rate of heating for a given profile can be controlled strictly. These forced convection ovens offer greater zone-to-zone stability, providing a level of control necessary to operate within the shrinking operating window made necessary by the implementation of lead-free solders.

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Question 9:
What are the performance differences among the solders?

To supplement the LCA information on tin-lead and lead-free solders, a literature review was conducted to gather information on the performance characteristics of the lead-free solders. Although research on the health and environmental impacts of lead-free solders is very limited outside this study, research of alternative solders' performance was found to be taking place on a large scale by multi-stakeholder partnerships and industry sectors, as well as academia. These studies, however, are difficult to compare. The studies differed in their focus and often considered different alloy combinations, as well as performance tests. Additionally, resulting data were presented in varying metrics. Such disparities in the available data hindered the comparability of performance results across sources. Most studies compared the performance of the alternative solders with existing SnPb alloy standards. The table below includes a list of the considered literature sources and a summary of the information presented in each source. Finally, the charts exhibited below present select comparative data.

Table 9.1. Summary of Alloy Properties by Source

Source	Alloy composition*	Comments
Tin-Copper		
Lau et al.	Eutectic Sn-Cu	< **Melting temperature** – highest < **Tensile strength** – lower than Sn-Ag and Sn-Pb < **Elongation** – higher than Sn-Ag and Sn-Pb < **Shear strength** – comparable with Sn-Pb < **Creep strength** – higher than 100Sn but lower than Sn-Ag-Cu (at 20 and 100^{0}C) < **Time to rupture** – higher than Sn-Ag-Cu but lower than Sn-40Pb (at 25 and 100^{0}C) < **Wetting properties** – can potentially replace Sn-Pb in wave and reflow processes < **Reflow spreading** – better than Sn-Ag but poorer than eutectic Sn-Pb < **Wave soldering** – good candidate < **Wettability** (when using an unactivated flux) – lower than Sn-Pb < **Fatigue resistance** – fairly good
Plumbridge, William J.	Sn-Cu	< **Tensile strength** – drops with increasing temperatures < **Strength** – weaker and more ductile than Sn-Ag-Cu and Sn-Pb < **Creep performance** (Sn-0.5Cu) – similar to Sn-37Pb and poorer than Sn-Ag-Cu (at 75^{0}C)
Grusd, Angela and Chris Jorgensen	Sn-0.7Cu	< **High-temperature applications** – suitable < **Creep/fatigue** – superior to Sn-Pb but inferior to Sn-Ag-*X*
Bath et al.	Sn-0.7Cu	< **Wave soldering** – best candidate (along with Sn-3.5Ag) < **Reflow applications** – undesirable < **Surface-mount use** – similar to eutectic Sn-Pb
Seelig, Karl and David Suraski	Sn-Cu	< **Melting temperature** – high; prohibits alloy use for temperature-sensitive applications < **Wetting** – poor (in comparison with other lead-free solders) < **Capillary action** – low when drawing into barrels during PTH technology < **Fatigue** – poor overall < **Surface-mount use** – lacks fatigue resistance needed < **Mechanical stresses** – weak; joint unable to withstand wide ranging mechanical stresses (cracked during mechanical strength-flex testing)
AIM(a)	Sn-0.7Cu	< **Cost** - effective < **Wave and hand soldering applications** – good alternative < **Wetting** – poor

Source	Alloy comp - osition*	Comments
	Tin -Copper	
AIM(a)	Sn-3Cu	< **High-temperature applications** - recommended (recommended against low-temperature application use)
	Tin-Silver-Copper	
Lau et al.	Sn-3.5Ag-0.9Cu	< **Tensile strength** – higher than eutectic Sn-Pb < **Strength (yield, shear, impact, creep resistance)** (alloys near eutectic Sn-Ag-Cu) – higher than Sn-Pb < **Tensile strength, shear strength, and melting temperature** (alloys further away from eutectic Sn-Ag-Cu) – increases whereas elongation decreases < **Creep** (Sn-3.5Ag-0.75Cu) – longest time to break in tests < **Wettability** (when using an unactivated flux) – lower than Sn-Pb but higher than Sn-Cu < **Notes** – prevailing alternative to lead-containing solder
Ochiai et al.	Sn-Ag-Cu	< **Deform** (plastically) – difficult; and less likely to **harden** < **Fatigue life** – longer than Sn-Pb (sufficient fatigue resistance for use in electronics assembly)
Plumbridge, William J.	Sn-Ag-Cu	< **Elongation to failure** – smallest < **Strength** – better than Sn-Cu and Sn-Pb < **Creep resistance** – much greater than Sn-37Pb < **Creep ductility** – lower than Sn-37Pb < **Note** (Sn-3.8Ag-0.7Cu, patented) **–** potentially most popular lead-free alloy
Kariya, Yoshiharu and William J. Plumbridge	Sn-3Ag-0.5Cu	< **Tensile strength** – decreases with increasing temperature and decreasing strain rate < **Tensile strength** – similar to Sn-3.8Ag-0.7Cu; superior than Sn-3.5Ag and Sn-0.5Cu (at 10^{-3}/s and 348K) < **Creep resistance** – comparable with Sn-3.8Ag-0.7Cu; superior to Sn-Ag
Sheng et al.	Sn-3.5Ag-0.5Cu	< **Mechanical properties** – comparable with Sn-37Pb < **Tensile and yield strength** – slightly lower than Sn-37Pb < **Creep performance** – superior to Sn-37Pb < **Wetting properties** – comparable with Sn-37Pb < **Viscosity (static and dynamic), tack, printability, solderability, wide reflow window and reflow characteristics** – similar to Sn-37Pb < **Print life** – larger than Sn-37Pb < **Note** – alloy paste usable in PCB applications
Grusd, Angela and Chris Jorgensen	Sn-4Ag-0.5Cu	< **High-temperature operations** (up to 175°C) – well-suited < **Mechanical stability** (joint) – degrades when the melting point is approached < **Wetting** (using commercial fluxes)– does not wet copper as well as eutectic Sn-Pb
Bath et al.	Sn-3.9Ag-0.6Cu	< **Reflow soldering** – preferred choice < **Solderability** – adequate; inferior to Sn-Pb < **Note** – in line with the International Tin Research Institute alloy range recommendation; thus qualifies for international standards
AIM(b)	Sn-3Ag-0.5Cu (LF218™)	< **Melting point** – low < **Cost** – lowest (from the Sn-Ag-Cu alloy family) < **Wetting** – best (from the Sn-Ag-Cu alloy family) < **Joint reliability** – excellent < **Flux types** – compatible with all types < **Mechanical fatigue resistance** – excellent < **Wave and hand soldering applications** – virtual drop-in for eutectic Sn-Pb < **Wave soldering characteristics** – produces less dross than other solder alloys; wets well; superior joint strength < **SMT applications use** – produces stronger solder joints; greater mechanical fatigue resistance; virtual drop-in for the eutectic Sn-Pb solder < **Note** – in line with JEIDA recommendation < **Note** – no-clean solder pastes pass all Bellcore and IPC specifications
AIM(a)	Sn-3Ag-0.5Cu (LF218™)	< **Note** – in line with JEIDA recommendation < **Cost** (from pure metals for this alloy) – lowest
AIM(b)	Sn-3.8-4Ag-0.5-0.7Cu (TSC-4)	< **Melting point** – low < **Wetting** – good < **Solder joint reliability** – excellent < **Flux type** – compatible with all < **Mechanical fatigue resistance** – excellent < **SMT application use** – virtual drop-in for eutectic Sn-Pb solders < **Note** – in line with the NEMI recommendation < **Note** – no-clean solder pastes pass all Bellcore and IPC specifications

Source	Alloy comp - osition*	Comments
		Tin-Silver-Copper
AIM(a)	Sn-3.8-4Ag-0.5-0.7Cu (TSC-4)	< **Characteristics** – similar to CASTIN® and LF218™ < **Cost** (of metals) – higher than CASTIN® and LF218™ < **Note** – presents potential silver phase change issues
AIM(a)	Sn-3.5Ag-0.5Cu	< **Characteristics** – similar to Sn-3Ag-0.5Cu < **Cost** (of metals) – slightly higher than Sn-3Ag-0.5Cu
Seelig, Karl and David Suraski	Sn-4Ag-0.5Cu	< **Fatigue** – good; superior thermal fatigue resistance when compared with Sn-Cu < **Joint strength** (overall) – good < **Thermal cycling characteristics** – some change in grain structure < **Mechanical strength** – passed all mechanical strength-flex test requirements < **Note** – sufficient supply of base materials
		Tin-Silver-Copper-Bismuth
Lau et al.	Sn-Ag-Cu-Bi	< **Surface tension, electrical resistivity, and density** – comparable with Sn-Ag, Sn-Ag-Cu and Sn-Ag-Cu-*X* < **Hardness** – superior to Sn-Pb < **Strength** (tensile and yield) – higher than Sn-Pb < **Elongation** – lower than Sn-Pb < **Creep** – slower rate than Sn-Pb < **Wetting behavior** – fairly comparable with Sn-37Pb (with 1 or 2% Bi-content). < **Creep resistance and wetting** – outstanding

*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.

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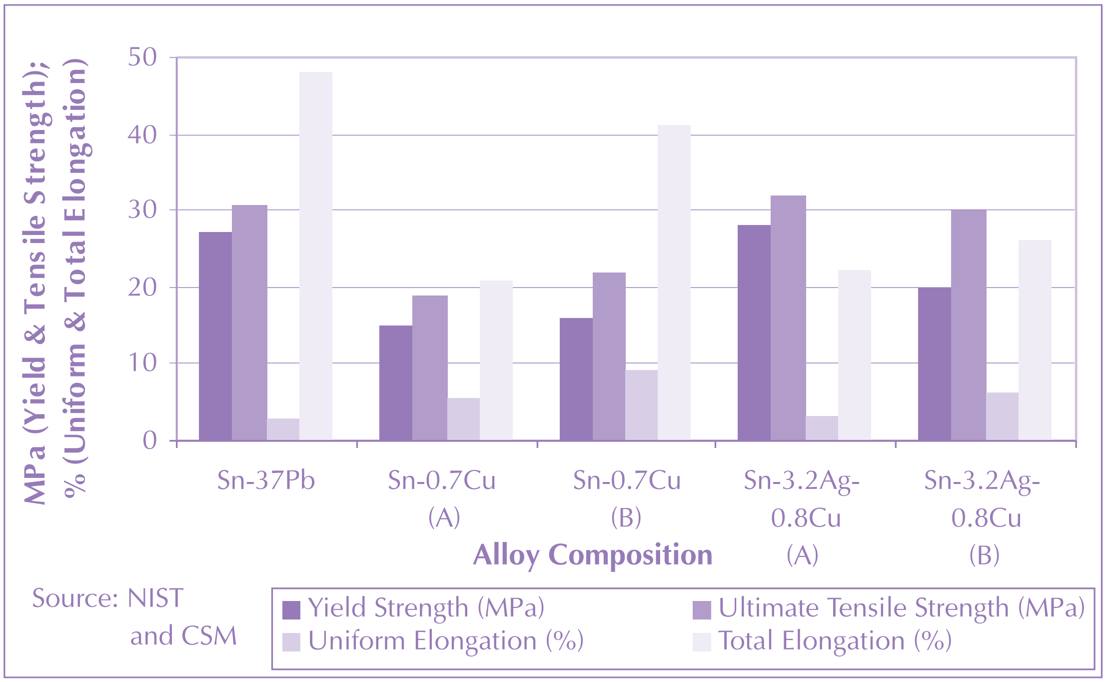
Comparison of Alloy Properties

This section presents samples of comparative alloy data for select performance properties by source. These data should not be compared across sources, without referencing back to the initial literature source, as performance tests carried out on alloys and metrics used to display data often differed.

NIST and CSM data (Figure 9.1) compare two alloys, SnCu and SnAgCu, with eutectic SnPb. Two processes were carried out on the two alloys: water-quenched and air-cooled. Although eutectic SnCu exhibited lower elongation than eutectic SnPb, air-cooled SnCu exhibited higher elongation than its water-quenched alloy and the SnAgCu alloy through both processes. Air-cooled SnAgCu exhibited higher tensile strength than both the alloys, whereas its elongation was lower than SnCu and similar to SnPb.

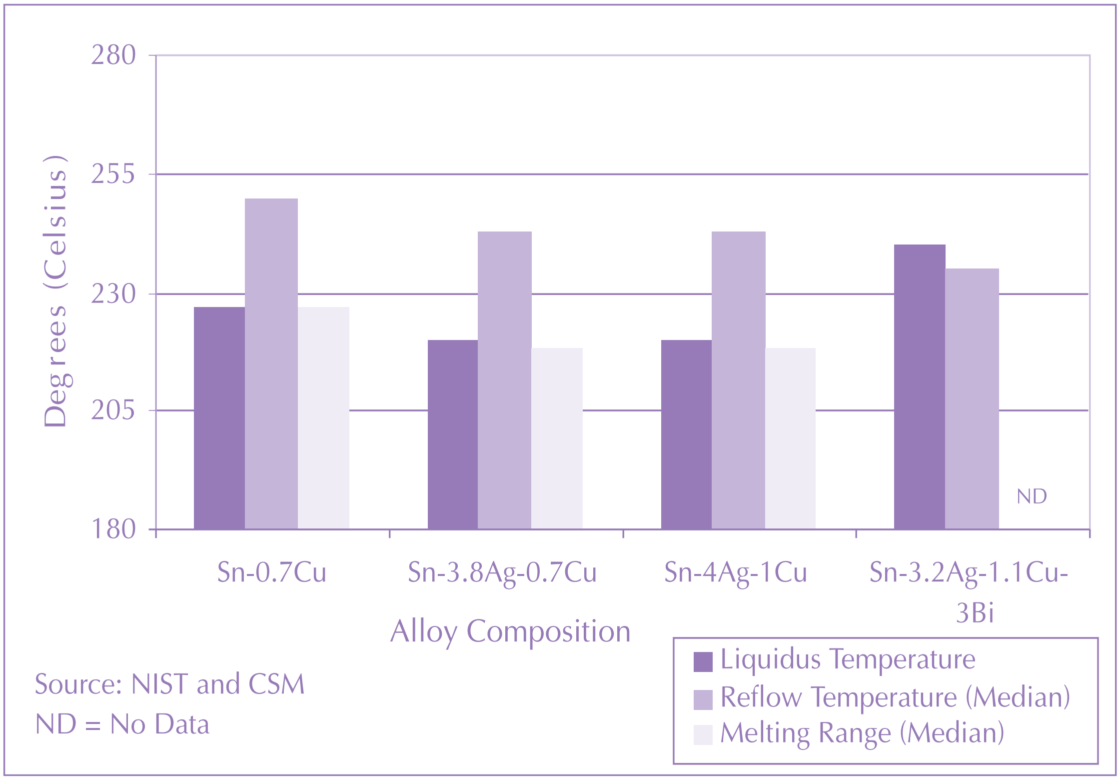
Figure 9.1. Mechanical Properties



Key: A = water-quenched average; B = air-cooled

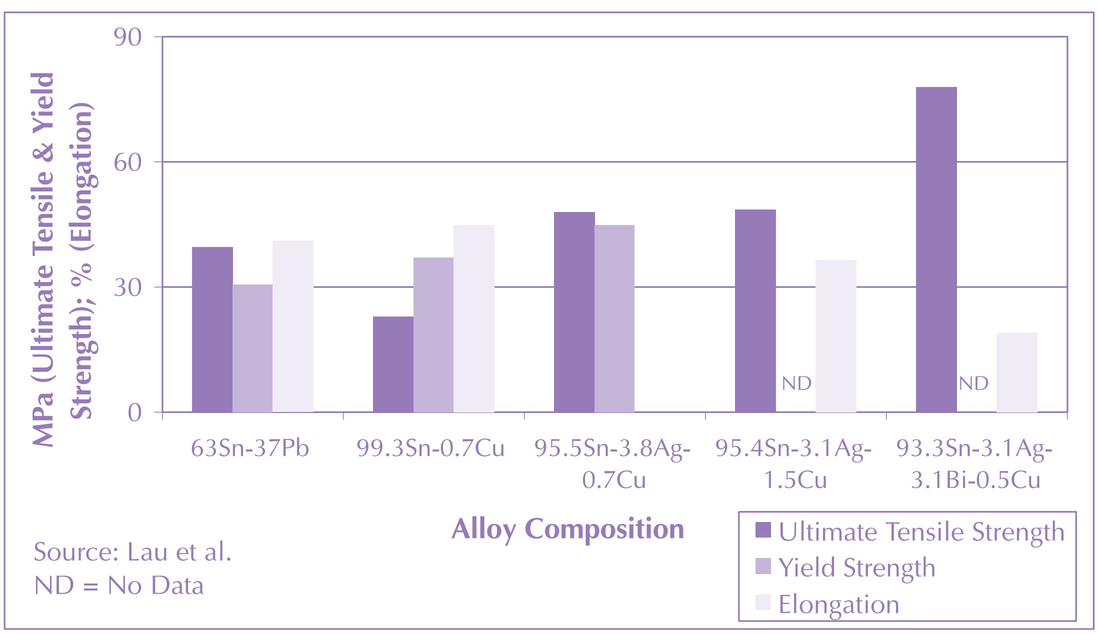
NIST and CSM data (Figure 9.2) also present that the reflow temperature and melting range of eutectic SnCu is the highest when compared with three other alloys (see below). Sn-3.2Ag-1.1Cu-3Bi is found to have the highest liquidous temperature, whereas all other alloys fall between 205-230°C. Reflow temperatures for all four alloys fall between 230-255°C.

Figure 9.2. Thermal Properties



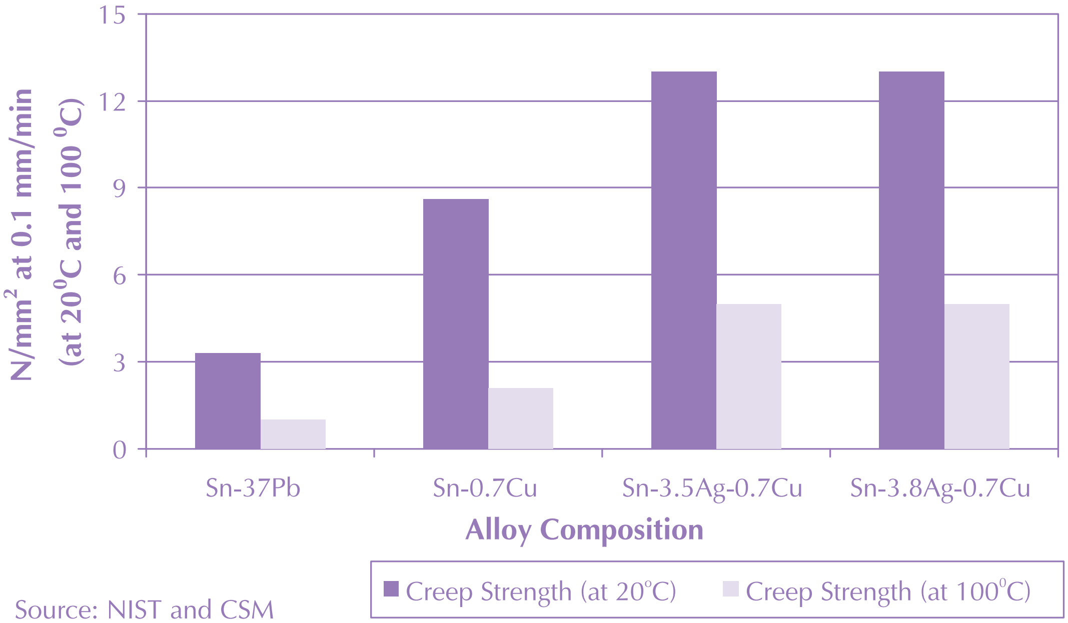
Lau et al. (Figure 9.3) present that eutectic SnCu is lower in tensile strength but higher in elongation than SnPb, reflecting its softness and ductility. The tensile strength of SnAgCu is higher than eutectic SnPb. SnAgCuBi alloys exhibit a higher tensile strength and a lower elongation as compared to eutectic SnPb.

Figure 9.3. Ultimate Tensile Strength, Yield Strength and Elongation



The exhibit of NIST and CSM data in Figure 9.4 presents that SnPb has the lowest creep strength when compared with SnCu and SnAgCu alloys, whereas SnAgCu presents the highest creep strength.

Figure 9.4. Creep Strength



Source: NIST and CSM

Question 10:
What are the potential market impacts of a switch to lead-free solders?

This section presents the costs associated with the changes in demand for solder metals that might result from a shift from lead-based solders to the lead-free solder alternatives considered in the LCA. First, the current use of lead-based solder is discussed. Second, the impacts of a U.S. conversion to lead-free solder alternatives are presented. Finally, market summaries are presented for the metals used in lead-free solders.

Current U.S. Use of Tin-Lead Solder

The current quantity of tin-lead solder used in electronic products is not available in the published literature. However, potential values of the amount of electronic solder consumed in the United States were developed from U.S. Geological Survey (USGS) tin and lead consumption data, expert opinion, and estimates of world production of tin-lead solder. The estimates of U.S. consumption of electrical solder range from 30 million pounds to 73 million pounds. Based on research done in 2002, EPA believed the most likely level to be between 35 million pounds and 42 million pounds. To avoid underestimating the magnitude of a switch from tin-lead solder to lead-free solder, EPA used a slightly conservative estimate of U.S. tin-lead solder consumption of 44 million pounds for this analysis. Worldwide estimates of tin-lead solder use in 2002 are over 176 million pounds.

Impact Analysis of a U.S. Conversion to Lead-Free Solders

This section evaluates the potential impacts on the U.S. markets for the alternative metals that could result from a U.S. conversion from tin-lead solder to four alternative lead-free solders. This analysis focuses on a conversion of solders used in electrical applications only, excluding uses for building construction, can and container manufacturing, and automobile assembly.

The first step of this analysis is an assessment of the change in quantities of alternative metals that might be demanded as a result of a conversion to lead-free solder. The current amount of tin-lead solder consumed in electronics products in the U.S., estimated to be 20,000 metric tons, is used along with the mass-based substitution ratios to calculate the equivalent amount of lead-free solder that would be needed as a substitute. For each constituent metal in the alternative solders being considered, the analysis calculates the additional quantity demanded.

The second step in the analysis is an assessment of the magnitude and the significance of the changes in the markets of the alternative metals. This is done by comparing the change in demand for each alternative metal to the current production, consumption, and existing stocks of that metal, for the United States and for the world. This comparison reveals the magnitude and importance of the change in the potential demand for each metal. Information on market trends is then used to frame the results in the dynamic context of changing markets.

Table 10.1 presents EPA's estimates of the change in demand for each metal used for the alternative solders. Using the information on solder composition and solder substitution ratios, this table converts the quantity of each metal currently used in tin-lead solder (column 1) into the quantity of each metal that would be demanded under the three alternatives (column 4). The difference between the two estimates is the change in the quantity of each metal that would be demanded if all use of tin-lead solder in the United States were discontinued (column 5) and shifted completely to any one of the lead-free solders. Column 7 presents the value of the change in metal demand, valued at year-2003 prices (column 6).

Table 10.1. Additional Quantities Demanded by a U.S. Conversion to Lead-Free Solder

	(1) Estimated baseline quantity [a] (metric tons)	(2) Post-conversion (%)	(3) Ratio of alternative to tin-lead solder by mass [b]	(4) Estimated post-conversion quantity [c] (metric tons)	(5) Estimated change in quantity [d] (metric tons)	(6) U.S. refined metal price in 2000 [e] ($/metric ton)	(7) Estimated value of change in quantity [f] (2003$)
SnCu Alternative:	**99.2% Tin and 0.8% Copper**						
Tin	12,600	99.2%	0.8320	16,508	3,908	$7,871	$30,755,580
Copper	0	0.8%	0.8320	133	133	$1,720	$228,925
SAC Alternative:	**95.5% Tin, 3.9% Silver, and 0.6% Copper**						
Tin	12,600	95.5%	0.8458	16,154	3,554	$7,871	$27,972,944
Silver	0	3.9%	0.8458	660	660	$149,822	$98,837,619
Copper	0	0.6%	0.8458	101	101	$1,720	$174,526
BSA Alternative:	**57% Bismuth, 42.0% Tin, and 1.0% Silver**						
Tin	12,600	42.0%	0.9942	8,351	-4,249	$7,871	-$33,442,217
Silver	0	1.0%	0.9942	199	199	$149,822	$29,789,495
Bismuth	0	57.0%	0.9942	11,333	11,333	$6,393	$72,459,159
SABC Alternative:	**96.0% Tin, 2.5% Silver, 1.0% Bismuth, and 0.5% Copper**						
Tin	12,600	96.0%	0.8433	16,192	3,592	$7,871	$28,270,655
Silver	0	2.5%	0.8433	422	422	$149,822	$63,175,045
Copper	0	0.5%	0.8433	84	84	$1,720	$145,020
Bismuth	0	1.0%	0.8433	169	169	$6,393	$1,078,353

[a] Estimated Baseline Quantity of Tin = 20,000 mton * 63%.

[b] The densities of lead, tin, silver, copper, and bismuth are 11.34, 7.31, 10.49, 8.92, and 9.78 g/cm^3, respectively. The density of the baseline solder, 63% tin and 37% lead, is 8.801 g/cm^3, or (0.37)11.34 + (0.63)7.31. The density is used to convert volume (functional unit) to mass.

[c] Estimated Post-Conversion Quantity = 20,000 metric tons * Post-Conversion % * Ratio of Alternative to Tin-Lead Solder by Mass.

[d] Estimated Change in Quantity = Estimated Post-Conversion Quantity - Estimated Baseline Quantity.

[e] Prices are as reported in the USGS Mineral Commodity Summaries, 2004. The tin price is the New York Composite average price. The silver price is from Handy and Harmon quotations. The copper price is the London Metals Exchange price. The bismuth price is the price received by domestic dealers.

[f] Estimated Value of Additional Quantity = Estimated Additional Quantity * U.S. Refined Metal Price in 2003.

Source: USGS Mineral Commodity Summaries 2004

Table 10.2 shows the magnitude of the change in metal demand under each alternative, relative to current U.S. production, consumption, and stocks of that metal. The table presents the estimated quantity of each metal that was produced, consumed, or held in stockpile in the United States in 2003 (columns 2, 4, and 6). It also shows the change in demand for the metals, both by weight (column 1, from Table 10.1 above) and as a percentage of current production, consumption, and stocks (columns 3, 5, and 7).

Table 10.2. Impacts of U.S. Conversion on U.S. Markets

	(1) Estimated additional quantity [a] (metric tons)	(2) 2000 U.S. refined production [b] (metric tons)	(3) Estimated % increase in U.S. refined production[c]	(4) 2000 U.S. refined consumption[d] (metric tons)	(5) Estimated % increase in U.S. refined consumption[e]	(6) 2000 U.S. refined stocks (metric tons)	(7) Estimated % of U.S. refined stocks[f]
SnCu Alternative:	**99.2% Tin and 0.8% Copper**						
Tin	3,908	11,000	36%	44,460	9%	10,100	39%
Copper	133	1,330,000	0.01%	2,270,000	0.01%	740,000	0.01%
SAC Alternative:	**95.5% Tin, 3.9% Silver, and 0.6% Copper**						
Tin	3,554	11,000	32%	44,460	8%	10,100	35%
Silver	660	3,800	17%	5,430	12%	3,480	19%
Copper	101	1,330,000	0.01%	2,270,000	0.004%	740,000	0.01%
BSA Alternative:	**57% Bismuth, 42.0% Tin, and 1.0% Silver**						
Tin	-4,249	11,000	-39%	44,460	-10%	10,100	-42%
Silver	199	3,800	5%	5,430	4%	3,480	6%
Bismuth	11,333	n.a.	n.a.	2,200	515%	100	11333%
SABC Alternative:	**96.0% Tin, 2.5% Silver, 1.0% Bismuth, and 0.5% Copper**						
Tin	3,592	11,000	33%	44,460	8%	10,100	36%
Silver	422	3,800	11%	5,430	8%	3,480	12%
Copper	84	1,330,000	0.01%	2,270,000	0.004%	740,000	0.01%
Bismuth	169	n.a	n.a	2,200	8%	100	169%

[a] Estimated Change in Quantity (demanded by a U.S. conversion to lead-free solder) from Table 10.1, column 5.
[b] Refined production quantities exclude mine production; copper scrap production is also excluded.
[c] Estimated % Increase in U.S. Refined Production = Estimated Additional Quantity / U.S. Refined Production.
[d] The reported production quantities are used for tin and bismuth; the production quantities for copper are the reported refined production quantities; the production quantity for silver is the apparent production.
[e] Estimated % Increase in U.S. Refined Consumption = Estimated Additional Quantity / U.S. Refined Consumption.
[f] Estimated % of U.S. Refined Stocks = Estimated Additional Quantity / U.S. Refined Stocks.

Source: USGS Mineral Commodity Summaries 2004.

A conversion to the SnCu alternative would result in the largest increases in demand for tin and copper. Converting to the SAC alternative would result in the largest increase in silver demand. The BSA alternative would lead to the largest bismuth demand increase, as well as a decline in tin demand. The decrease in demand for lead as a result of any of the conversions would be 12,600 metric tons, with an estimated value of $5,972,322.[1]

[1] The London Metal Exchange price of lead in 2003 was $474 per metric ton.

If all U.S. tin-lead solder used in electronics applications were replaced by any alternative containing Bi, the impact on the market for bismuth could be very large and Bi mines would have to increase their output. A conversion to lead-free solder could also have a significant impact on silver markets, which would lead to an increase in silver production. Three of the lead-free solders use significantly more tin than the current tin-lead solder and one uses significantly less. Therefore, the impact of a switch to lead-free solders on the tin market is unclear. Copper is used in three of the lead-free solder alternatives, but in very small quantities; therefore, a U.S. conversion to lead-free solder would have almost no effect on U.S. copper markets. Existing above-ground stocks would be sufficient to meet this small increase in demand for copper.