Chapter 3

LIFE-CYCLE IMPACT ASSESSMENT

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

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

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

3.1 METHODOLOGY

In its simplest form, LCIA is the evaluation of potential impacts to any system as a result of some action. LCIAs generally classify the consumption and loading data from the inventory stage to various impact categories. Characterization methods are used to quantify the magnitude of the contribution that loading or consumption could have in producing the associated impact. LCIA does not seek to determine actual impacts, but rather to link the data gathered from the LCI to impact categories and to quantify the relative magnitude of contribution to the impact category (Fava *et al.*, 1993; Barnthouse *et al.*, 1997). Further, impacts in different impact categories are generally calculated based on differing scales and, therefore, cannot be directly compared.

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

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

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

3.1.1 Classification

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

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

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

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

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

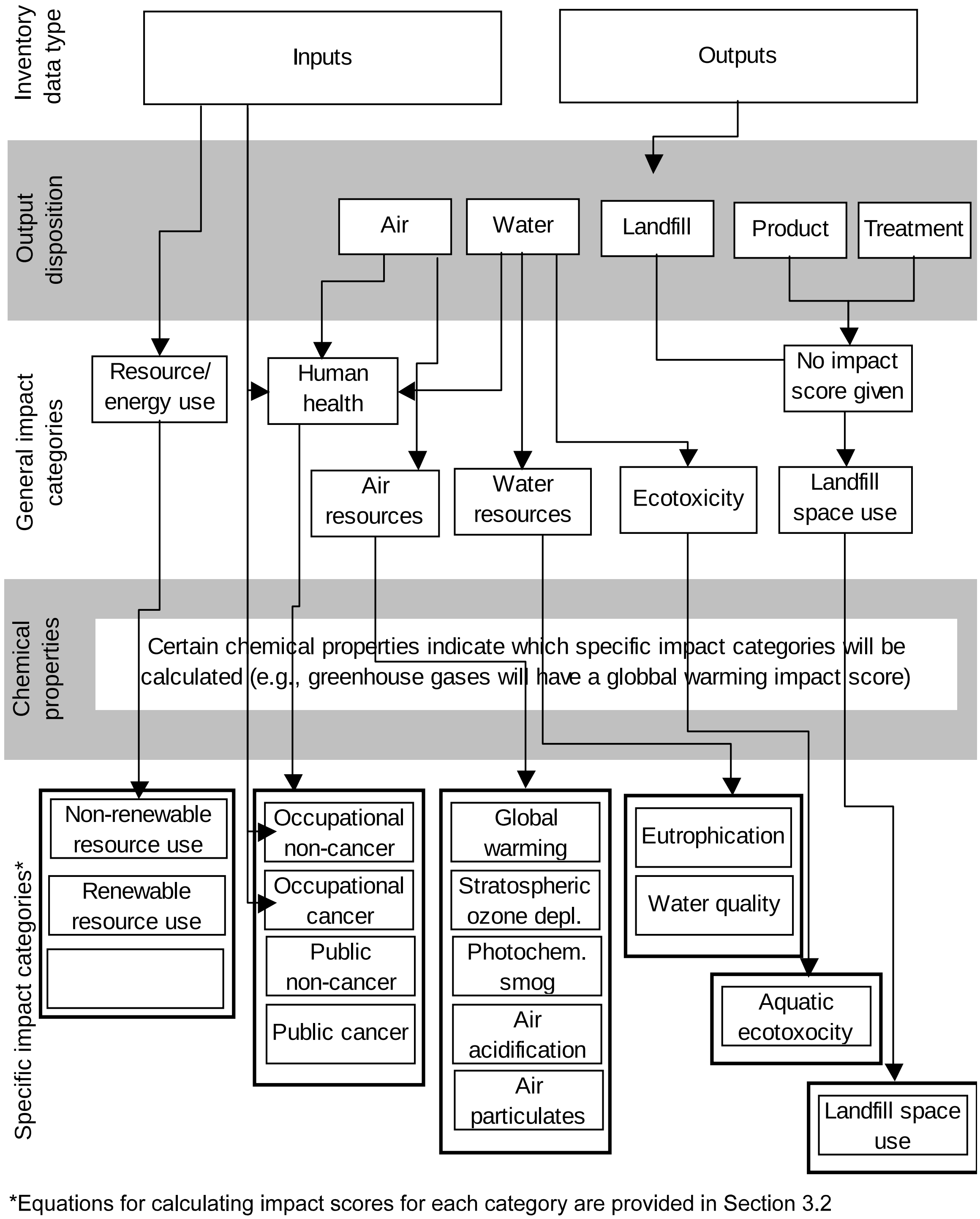

Figure 3-1. Impact Classification Conceptual Model

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

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

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

3.1.2 Characterization

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

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

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

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

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

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

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

Table 3-2. LCIA characterization approaches for the LFSP

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

3.2 CHARACTERIZATION AND RESULTS

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

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

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

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

Table 3-3. Process groups

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

3.2.1 Resource Use (Non-renewable and Renewable)

3.2.1.1 Characterization

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

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

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

where:

IS_{NRR}	equals the impact score for use of non-renewable resource *i* (kg) per functional unit;
Amt_{NRR}	equals the inventory input amount of non-renewable resource *i* (kg) per functional unit; and
RC	equals the fraction recycled content (post-industrial and post-consumer) of resource *i*.

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

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

where:

IS_{RR}	equals the impact score for use of renewable resource *i* (kg) per functional unit;
Amt_{RR}	equals the inventory input amount of renewable resource *i* (kg) per functional unit; and
RC	equals the fraction recycled content (post-industrial and post-consumer) of resource *i*.

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

3.2.1.2 Paste solder results

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

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

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

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

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

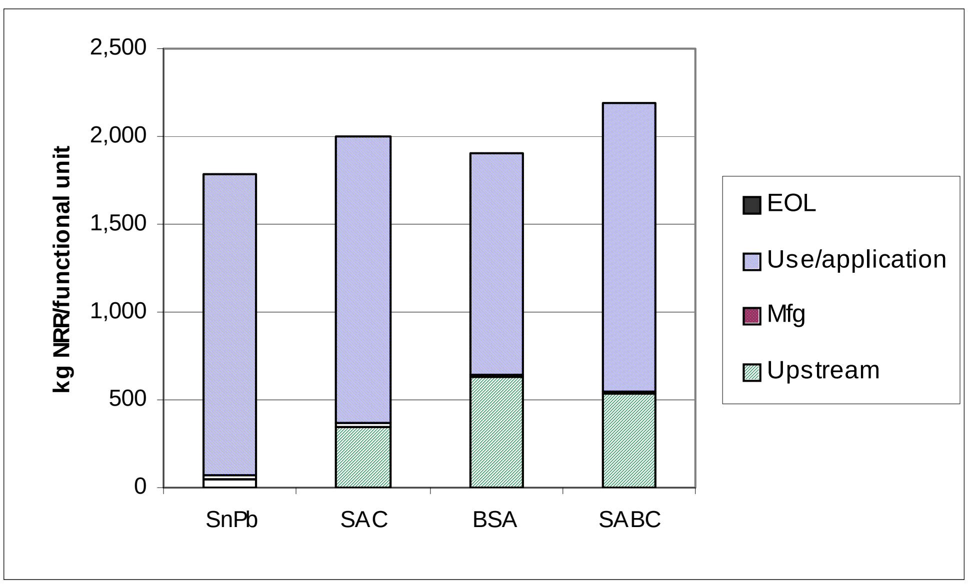

Figure 3-2. Solder Paste Total Life-Cycle Impacts: NRR Use

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

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

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

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

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

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

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

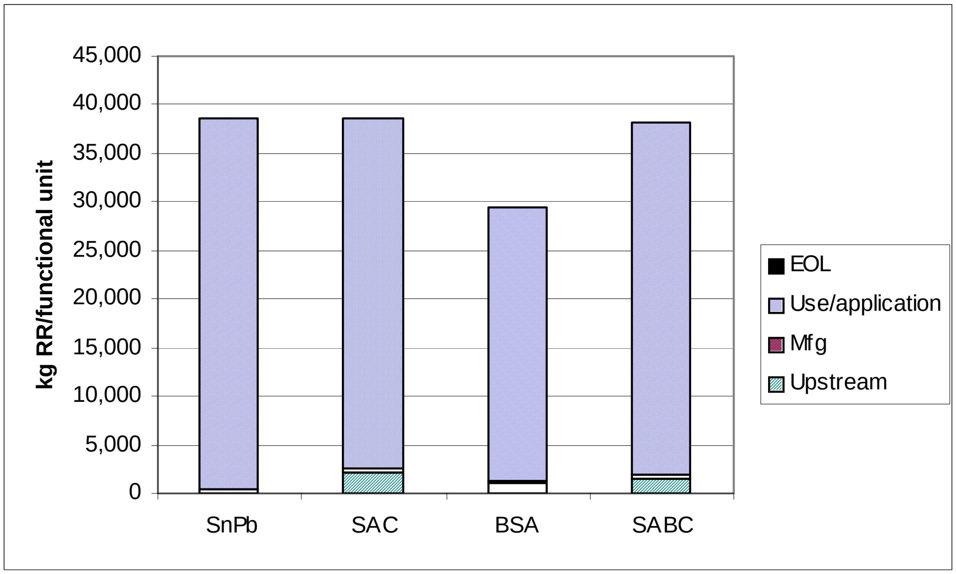

Figure 3-3 Solder Paste Total Life-Cycle Impacts: RR Use

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

Resource Use Impacts by Process Group (Paste Solder)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Top Contributors to Resource Use Impacts (Paste Solder)

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

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

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

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

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

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

3.2.1.3 Bar solder results

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

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

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

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

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

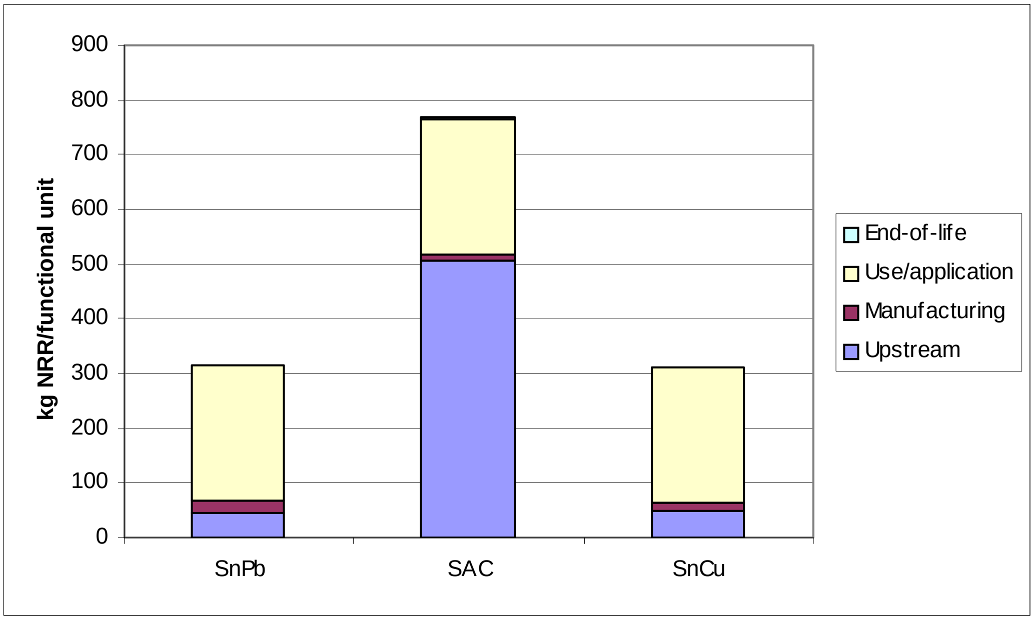

Figure 3-4. Bar Solder Total Life-Cycle Impacts: NRR Use

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

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

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

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

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

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

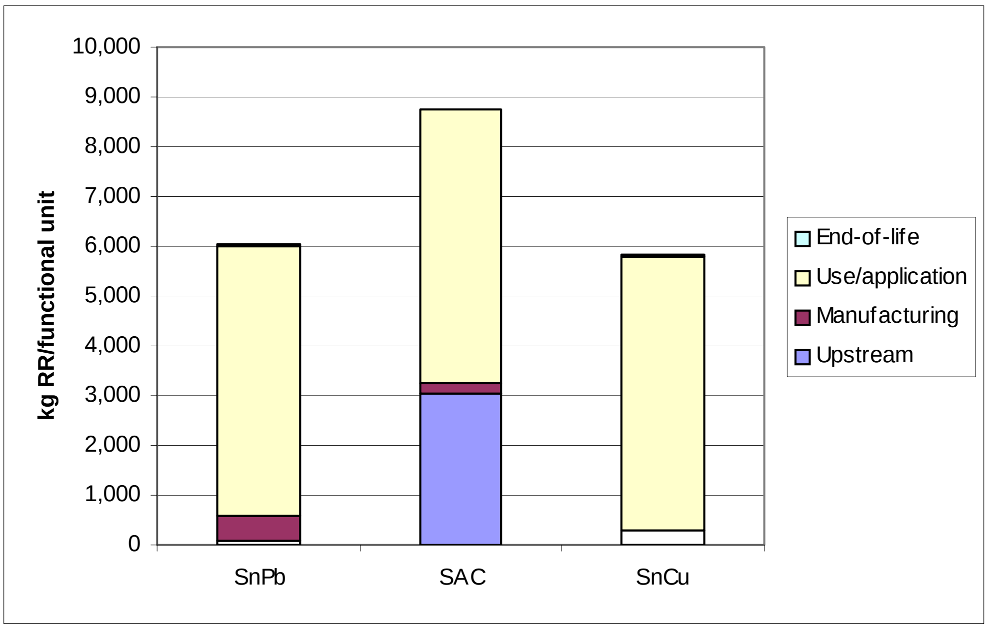


Figure 3-5. Bar Solder Total Life-Cycle Impacts: RR Use

Resource Use Impacts by Process Group (Bar Solder)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Top Contributors to Resource Use Impacts (Bar Solder)

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

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

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

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

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

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

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

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

3.2.1.4 Limitations and uncertainties

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

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

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

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

3.2.2 Energy Use

3.2.2.1 Characterization

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

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

where:

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

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

3.2.2.2 Paste solder results

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

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

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

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

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

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

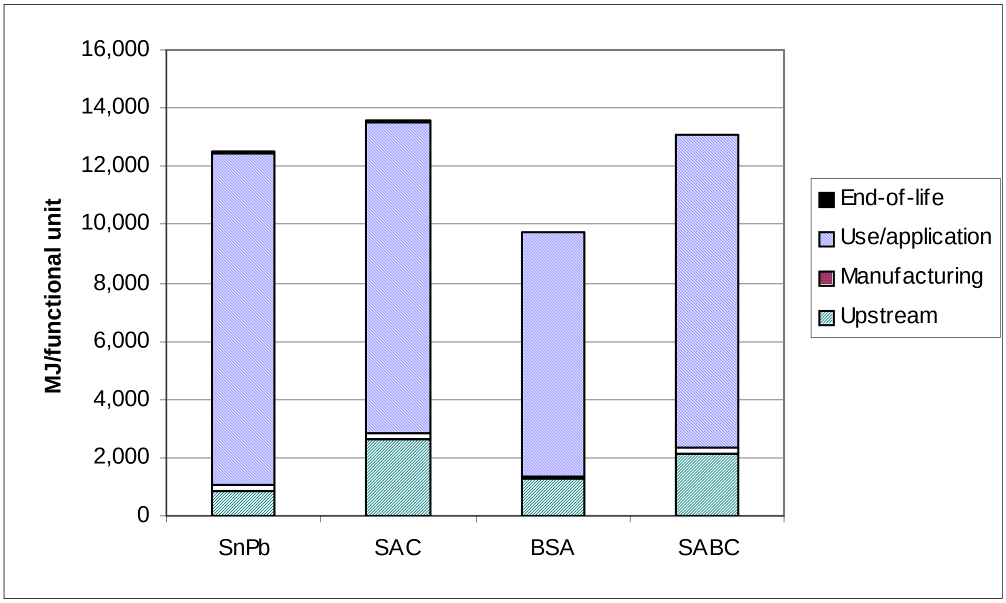


Figure 3-6. Paste Solder Total Life-Cycle Impacts: Energy Use

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

Energy Use Impacts by Process Group (Paste Solder)

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

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

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

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

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

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

Top Contributors to Energy Use Impacts (Paste Solder)

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

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

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

3.2.2.3 Bar solder results

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

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

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

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

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

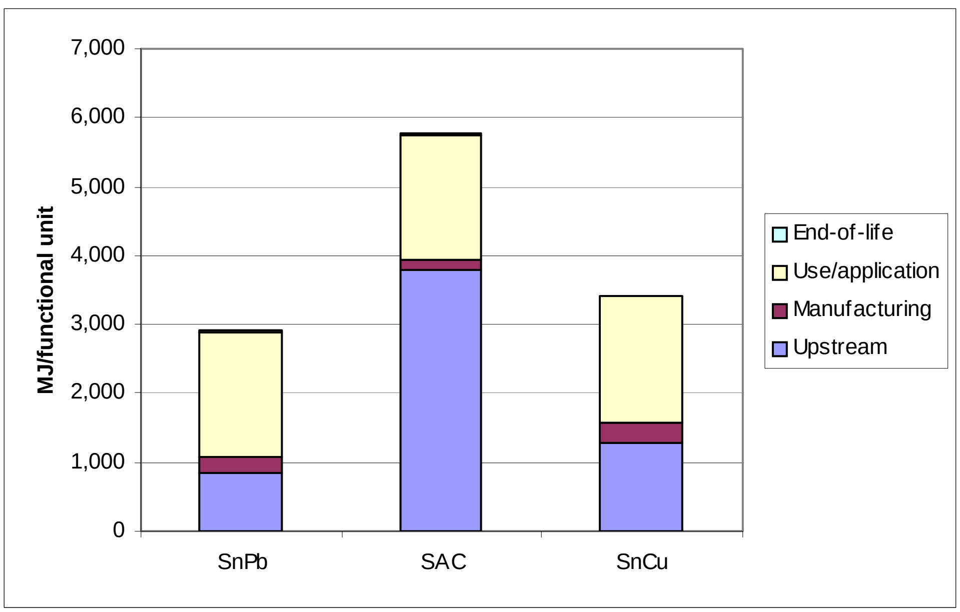


Figure 3-7. Bar Solder Total Life-Cycle Impacts: Energy Use

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

Energy Use Impacts by Process Group (Bar Solder)

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

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

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

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

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

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

Top Contributors to Energy Use Impacts (Bar Solder)

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

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

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

3.2.2.4 Limitations and uncertainties

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

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

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

3.2.3 Landfill Space Use Impacts

3.2.3.1 Characterization

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

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

where:

IS_L equals the impact score for landfill (L) use for waste *i* cubic meters (m^3) per functional unit;

Amt_W equals the inventory output amount of solid waste *i* (kg) per functional unit; and

D equals density of waste *i* (kg/m^3).

3.2.3.2 Paste solder results

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

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

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

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

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

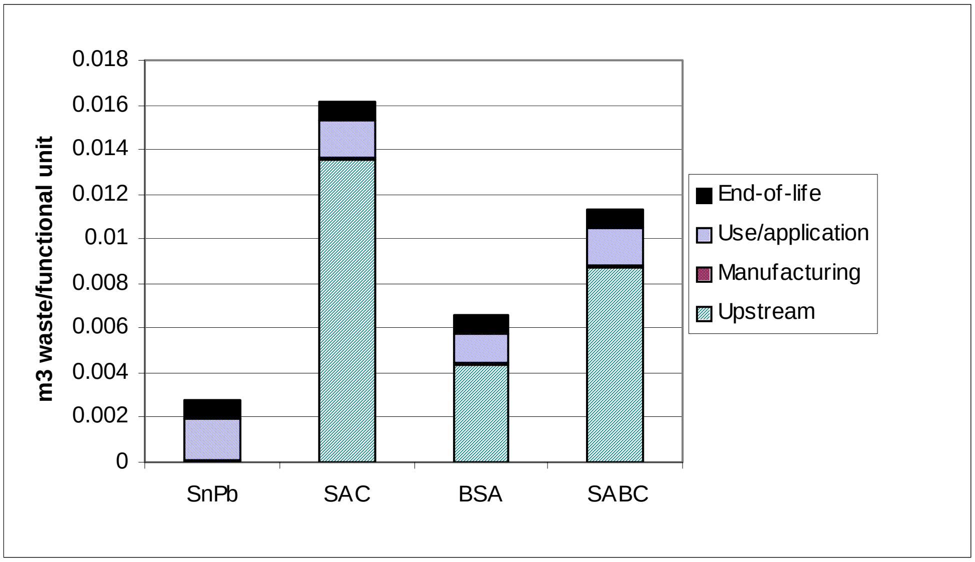


Figure 3-8. Paste Solder Total Life-Cycle Impacts: Landfill Space Use

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

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

Landfill Space Use Impacts by Process Group (Paste Solder)

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

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

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

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

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

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

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

Top Contributors to Landfill Space Use Impacts (Paste Solder)

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

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

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

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

<u>3.2.3.3 Bar solder results</u>

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

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

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

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

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

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

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

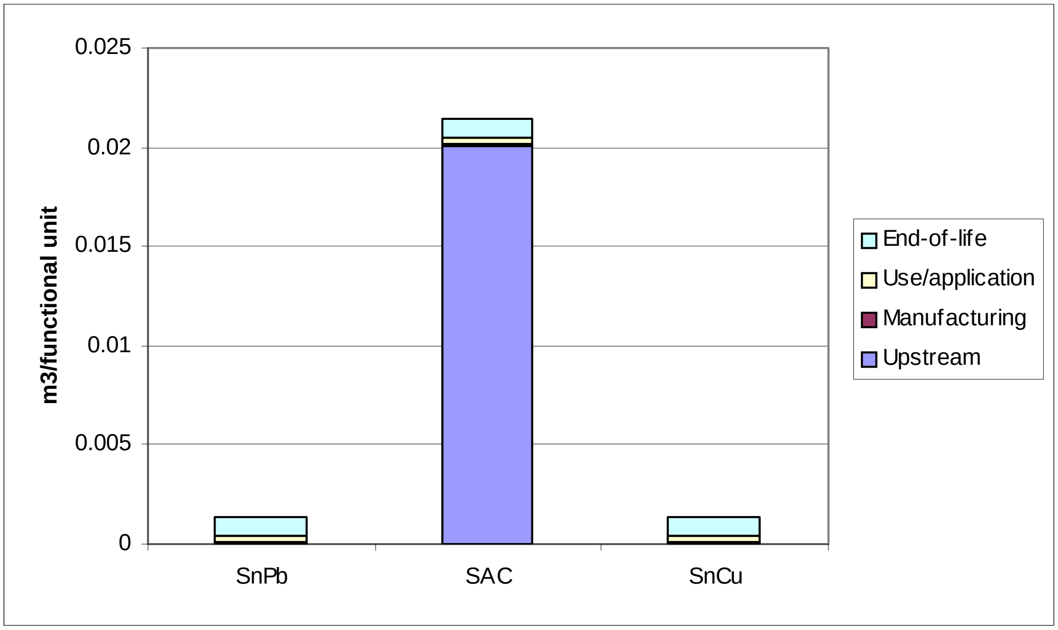


Figure 3-9. Bar Solder Total Life-Cycle Impacts: Landfill Space Use

Landfill Space Use Impacts by Process Group (Bar Solder)

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

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

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

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

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

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

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

Top Contributors to Landfill Space Use Impacts (Bar Solder)

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

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

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

3.2.3.4 Limitations and uncertainties

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

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

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

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

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

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

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

3.2.4 Global Warming Impacts

3.2.4.1 Characterization

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

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

where:

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

3.2.4.2 Paste solder results

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

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

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

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

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

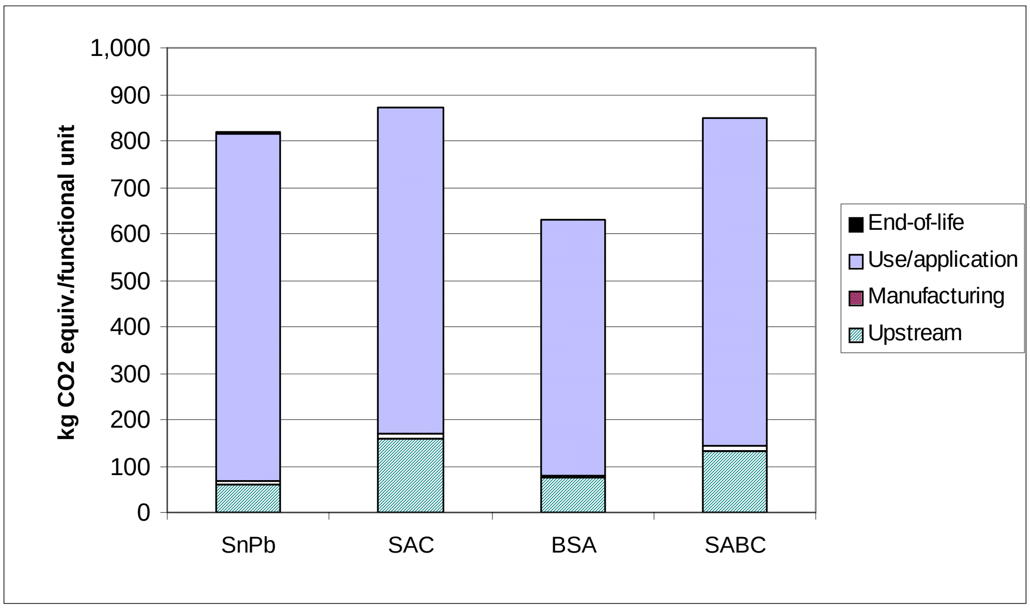


Figure 3-10. Solder Paste Total Life-Cycle Impacts: Global Warming

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

Global Warming Impacts by Process Group (Paste Solder)

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

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

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

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

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

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

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

Top Contributors to Global Warming Impacts (Paste Solder)

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

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

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

3.2.4.3 Bar solder results

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

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

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

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

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

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

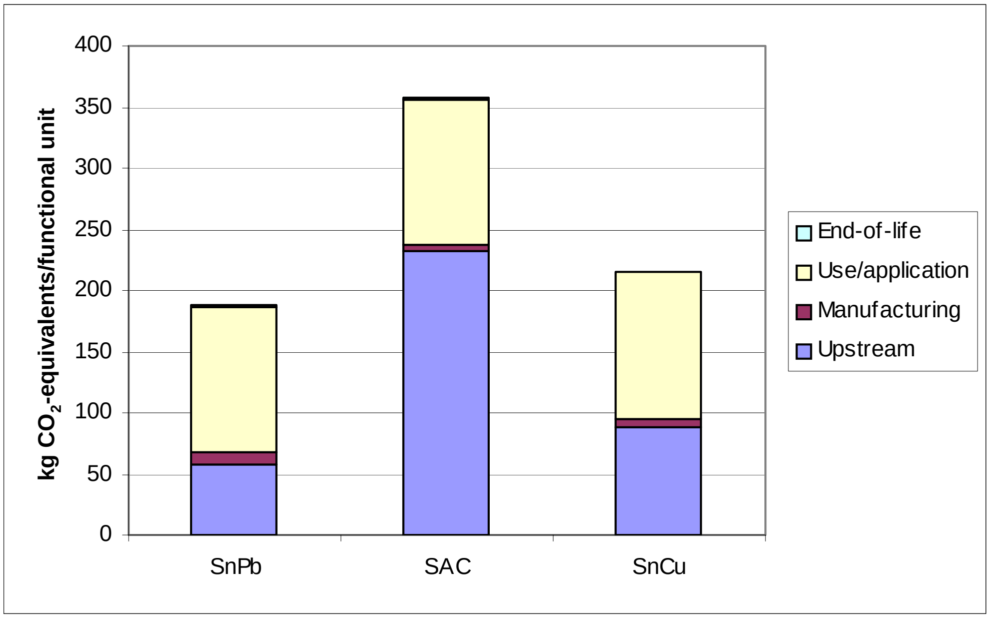


Figure 3-11. Bar Solder Total Life-Cycle Impacts: Global Warming

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

Global Warming Impacts by Process Group (Bar Solder)

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

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

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

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

Global warming impacts from the manufacturing life-cycle stage are small compared to the upstream and use/application life-cycle stages and are nearly evenly distributed between solder manufacturing and post-industrial recycling, with the exception of SnPb. Global warming impacts from the use/application stage are due entirely to the electricity consumed in the wave solder application process. These impacts are less dominant for bar solders than for the solder pastes, due to the reduced energy consumption per functional unit required by the wave process when compared to reflow assembly. For example, the global warming impacts for SnPb solder paste of 832 kg CO_2-equivalents greatly exceed the 119 kg CO_2-equivalents of global warming impacts for the wave application of SnPb bar solders.

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

Top Contributors to Global Warming Impacts (Bar Solder)

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

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

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

3.2.4.4 Limitations and uncertainties

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

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

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

3.2.5 Stratospheric Ozone Depletion Impacts

3.2.5.1 Characterization

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

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

where:

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

3.2.5.2 Paste solder results

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

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

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

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

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

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

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

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

Stratospheric Ozone Depletion Impacts by Process Group (Paste Solder)

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

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

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

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

*The impact scores are in units of kilograms CFC-11-equivalents/1,000 cubic centimeters of solder applied to a printed wiring board.
N/A=not applicable

Top Contributors to Stratospheric Ozone Depletion Impacts (Paste Solder)

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

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

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

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

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

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

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

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

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

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

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

3.2.5.3 Bar solder results

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

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

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

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

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

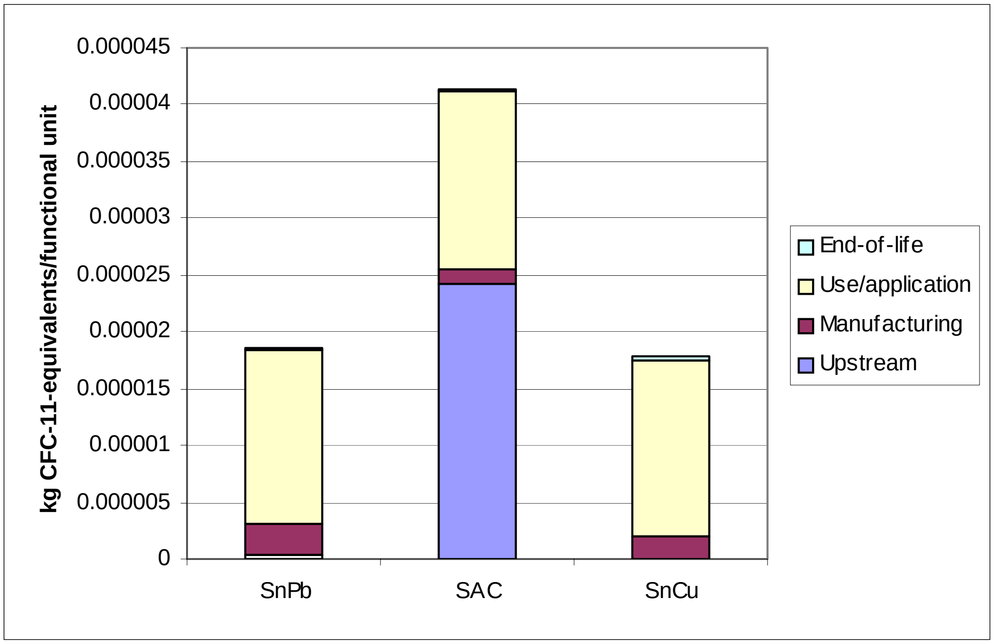


Figure 3-13. Bar Solder Total Life-Cycle Impacts: Stratospheric Ozone Depletion

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

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

Stratospheric Ozone Depletion Impacts by Process Group (Bar Solder)

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

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

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

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

*The impact scores are in units of kilograms CFC-11-equivalents/1,000 cubic centimeters of bar solder applied to a printed wiring board.
N/A=not applicable

Top Contributors to Stratospheric Ozone Depletion Impacts (Bar Solder)

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

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

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

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

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

3.2.5.4 Limitations and uncertainties

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

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

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

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

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

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

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

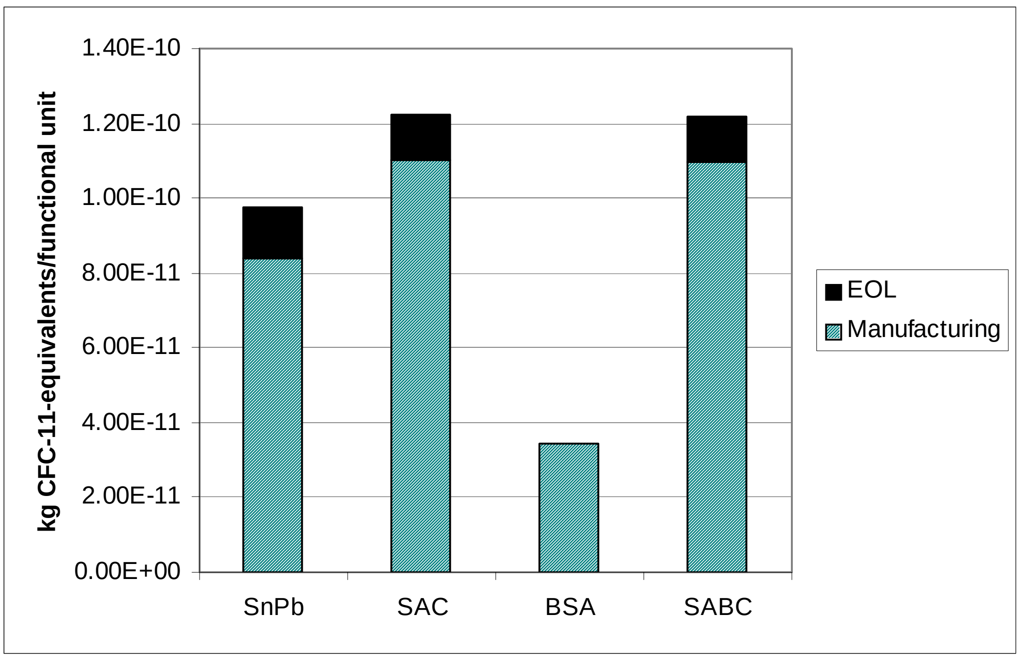


Figure 3-14. Ozone Depletion Impacts with Methyl Bromide Only (Paste Solder)

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

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

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

3.2.6 Photochemical Smog Impacts

3.2.6.1 Characterization

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

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

where:

IS_{POCP} equals the photochemical smog (POCP) impact score for chemical *i* (kg ethene equivalents) per functional unit;

EF_{POCP} equals the POCP equivalency factor for chemical *i* (ethene equivalents) (Appendix D); and

Amt_{POC} equals the amount of photochemical smog-creating oxidant *i* released to the air (kg) per functional unit.

3.2.6.2 Paste solder results

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

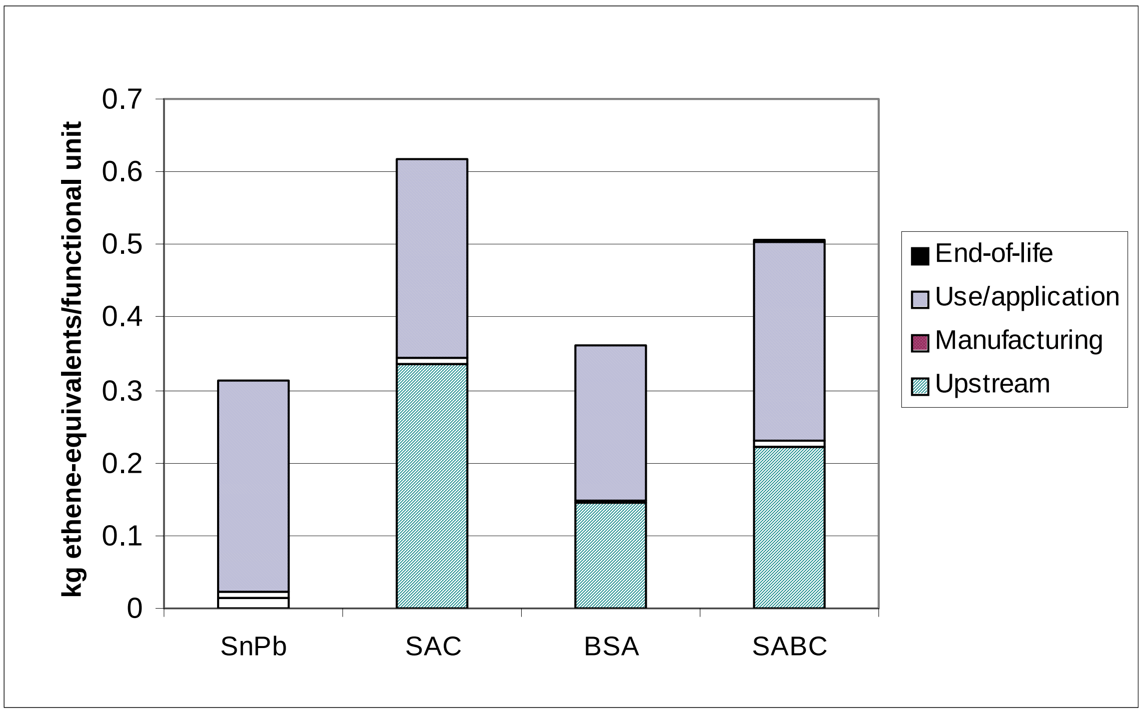
Table 3-42 presents the solder paste results for photochemical smog impacts by life-cycle stage based on the impact assessment methodology. The table lists the photochemical smog impact scores per functional unit for the life-cycle stages of each alloy, as well as the percent contribution of each life-cycle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

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

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

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

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



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

Photochemical Smog Impacts by Process Group (Paste Solder)

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

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

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

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

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

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

Top Contributors to Photochemical Smog Impacts (Paste Solder)

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

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

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

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

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

3.2.6.3 Bar solder results

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

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

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

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

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

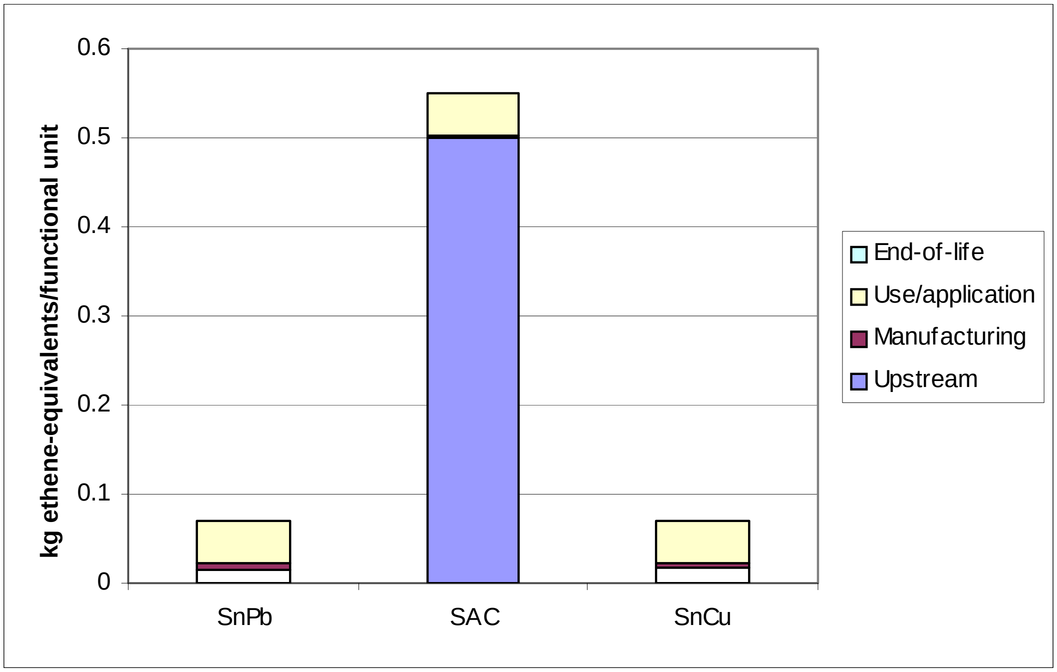


Figure 3-16. Bar Solder Total Life-Cycle Impacts: Photochemical Smog

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

Photochemical Smog Impacts by Process Group (Bar Solder)

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

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

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

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

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

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

Top Contributors to Photochemical Smog Impacts (Bar Solder)

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

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

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

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

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

3.2.6.4 Limitations and uncertainties

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

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

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

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

3.2.7 Acidification Impacts

3.2.7.1 Characterization

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

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

where:

IS_{AP} equals the impact score for acidification for chemical *i* (kg SO_2 equivalents) per functional unit;

EF_{AP} equals the AP equivalency factor for chemical *i* (SO_2 equivalents) (Appendix D); and

Amt_{AC} equals the amount of acidification chemical *i* released to the air (kg) per functional unit.

3.2.7.2 Paste solder results

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

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

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

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

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

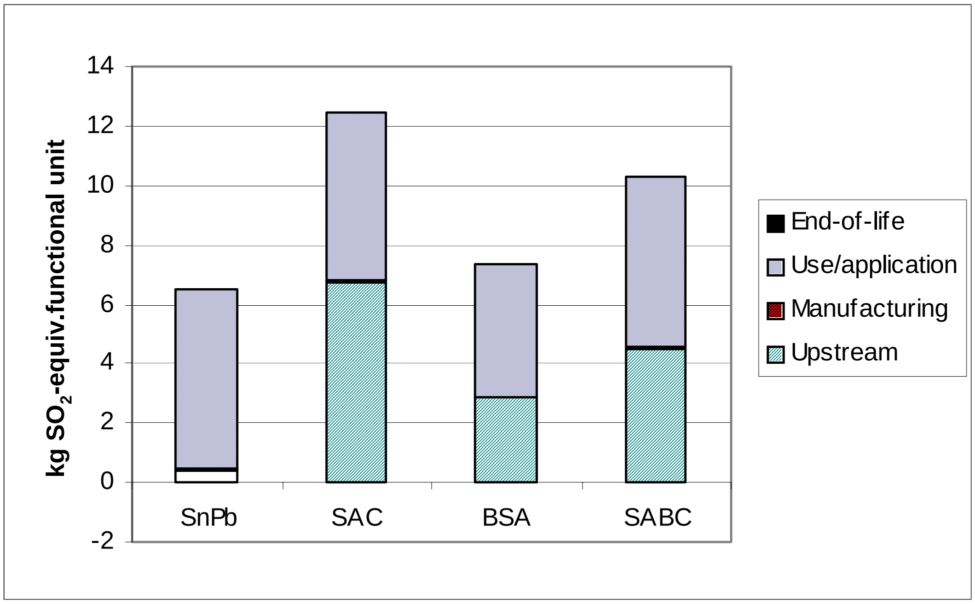


Figure 3-17. Solder Paste Total Life-Cycle Impacts: Acidification

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

Acidification Impacts by Process Group (Paste Solder)

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

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

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

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

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

Top Contributors to Acidification Impacts (Paste Solder)

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

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

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

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

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

3.2.7.3 Bar solder results

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

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

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

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

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

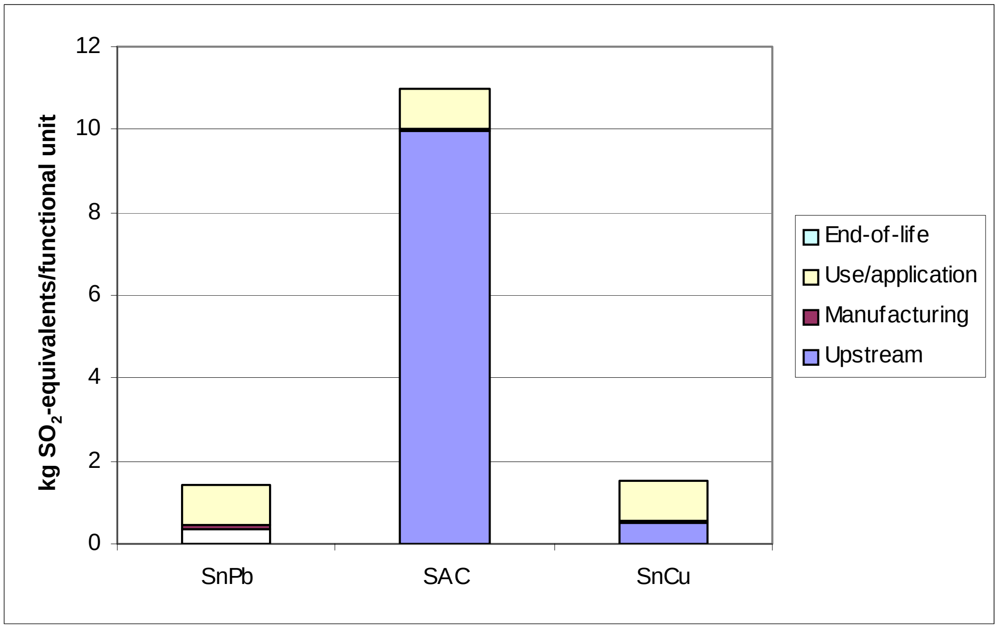


Figure 3-18. Bar Solder Total Life-Cycle Impacts: Acidification

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

Acidification Impacts by Process Group (Bar Solder)

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

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

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

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

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

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

Top Contributors to Acidification Impacts (Bar Solder)

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

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

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

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

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

3.2.7.4 Limitations and uncertainties

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

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

3.2.8 Air Particulate Impacts

3.2.8.1 Characterization

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

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

where:

IS_{PM} equals the impact score for particulate (kg PM_{10}) per functional unit, and

Amt_{PM} equals the inventory amount of particulate release (PM_{10}) to the air (kg) per functional unit.

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

3.2.8.2 Paste solder results

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

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

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

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

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

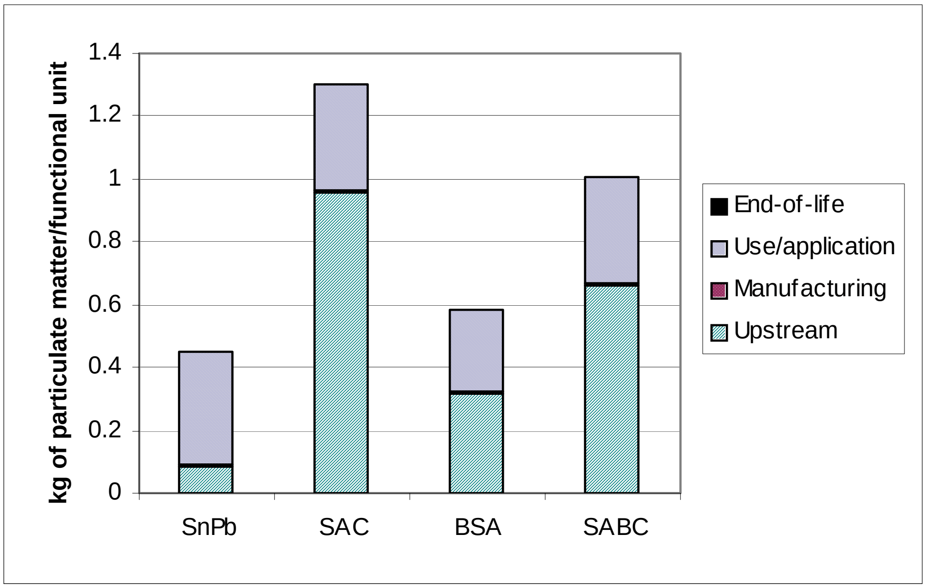


Figure 3-19. Solder Paste Total Life-Cycle Impacts: Air Particulates

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

Air Particulate Impacts by Process Group (Paste Solder)

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

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

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

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

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

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

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

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

Top Contributors to Air Particulate Impacts (Paste Solder)

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

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

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

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

3.2.8.3 Bar solder results

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

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

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

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

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

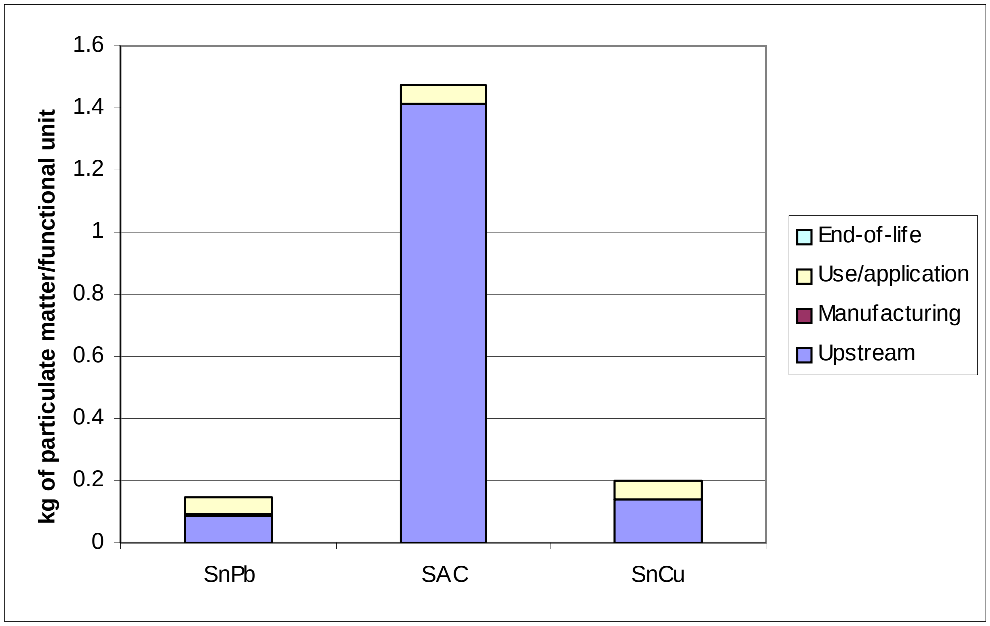


Figure 3-20. Bar Solder Total Life-Cycle Impacts: Air Particulates

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

Air Particulate Impacts by Process Group (Bar Solder)

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

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

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

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

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

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

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

Top Contributors to Air Particulate Impacts (Bar Solder)

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

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

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

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

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

3.2.8.4 Limitations and uncertainties

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

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

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

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

3.2.9 Water Eutrophication Impacts

3.2.9.1 Characterization

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

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

where:

IS_{EUTR} equals the impact score for regional water quality impacts from chemical *i* (kg phosphate equivalents) per functional unit;

EF_{EP} equals the EP equivalency factor for chemical *i* (phosphate equivalents) (Appendix D); and

Amt_{EC} equals the inventory mass (kg) of chemical *i* per functional unit of eutrophication chemical in a wastewater stream released to surface water after any treatment, if applicable.

3.2.9.2 Paste solder results

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

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

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

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

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

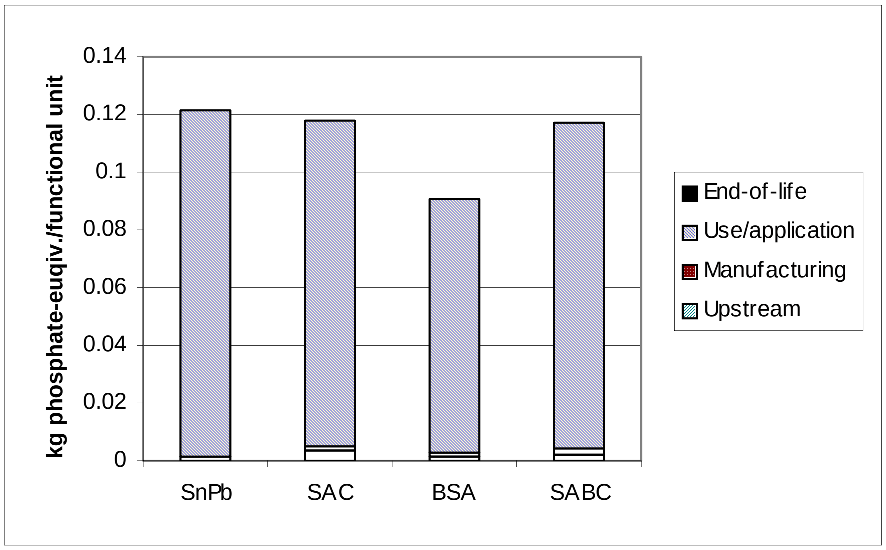


Figure 3-21. Solder Paste Total Life-Cycle Impacts: Water Eutrophication

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

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

Water Eutrophication Impacts by Process Group (Paste Solder)

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

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

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

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

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

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

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

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

Top Contributors to Eutrophication Impacts (Paste Solder)

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

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

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

3.2.9.3 Bar solder results

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

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

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

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

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

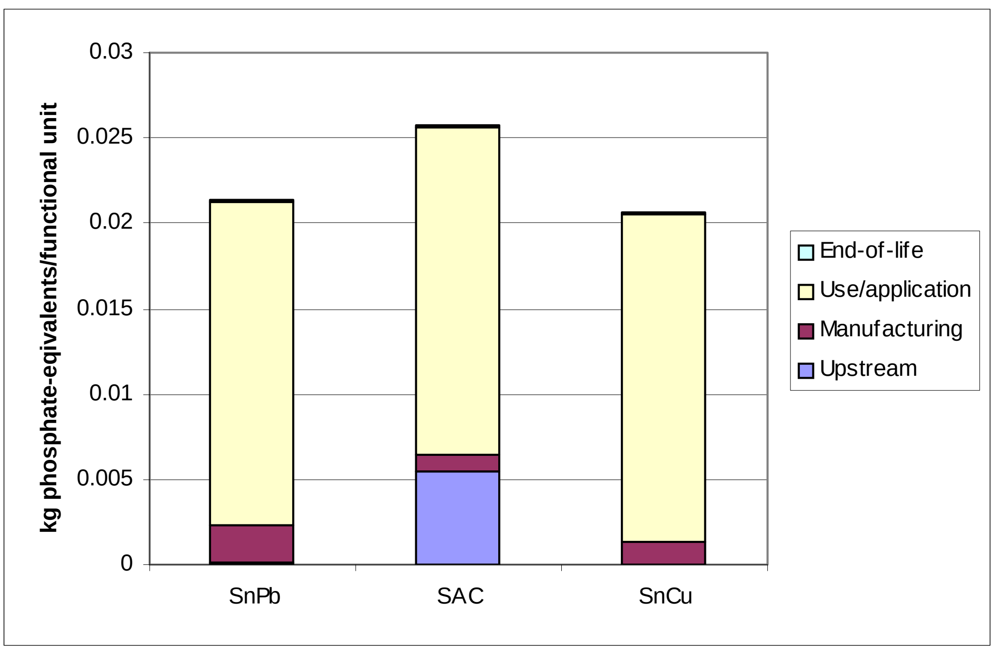


Figure 3-22. Bar Solder Total Life-Cycle Impacts: Water Eutrophication

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

Water Eutrophication Impacts by Process Group (Bar Solder)

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

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

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

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

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

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

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

Top Contributors to Eutrophication Impacts (Bar Solder)

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

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

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

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

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

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

3.2.9.4 Limitations and uncertainties

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

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

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

3.2.10 Water Quality Impacts

3.2.10.1 Characterization

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

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

and

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

where:

IS_{BOD} equals the impact score for BOD water quality impacts for waste stream *i* (kg) per functional unit;

Amt_{BOD} equals the inventory amount of BOD in wastewater stream *i* released to surface waters (kg) per functional unit;

IS_{TSS} equals the impact score for TSS water quality impacts for waste stream *i* (kg) per functional unit; and

Amt_{TSS} equals the inventory amount of TSS in wastewater stream *i* released to surface waters (kg) per functional unit.

3.2.10.2 Paste solder results

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

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

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

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

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

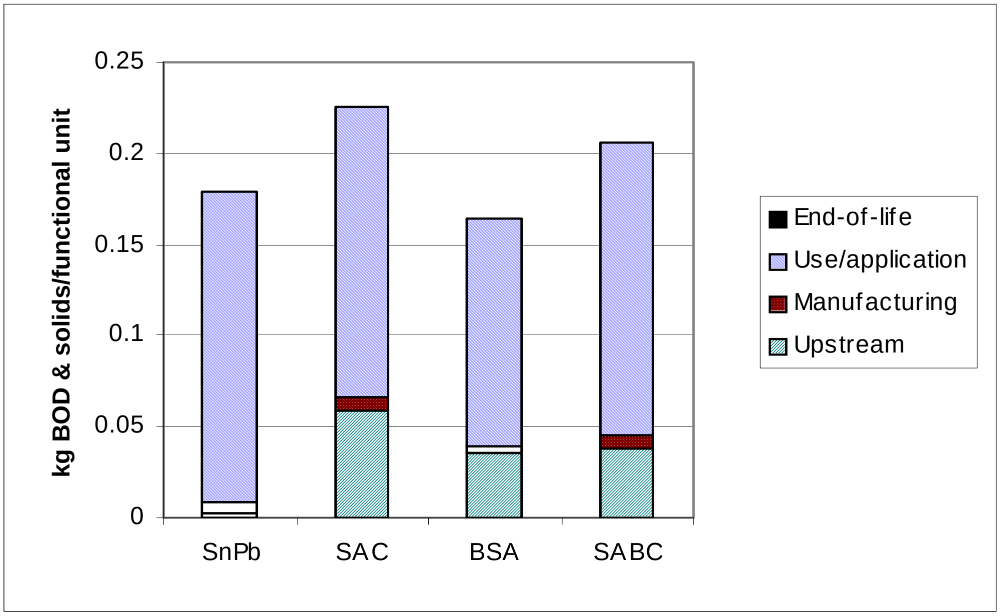


Figure 3-23. Solder Paste Total Life-Cycle Impacts: Water Quality (BOD & Solids)

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

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

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

Water Quality Impacts by Process Group (Paste Solder)

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

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

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

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

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

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

Top Contributors to Water Quality Impacts (Paste Solder)

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

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

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

<u>3.2.10.3 Bar solder results</u>

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

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

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

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

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

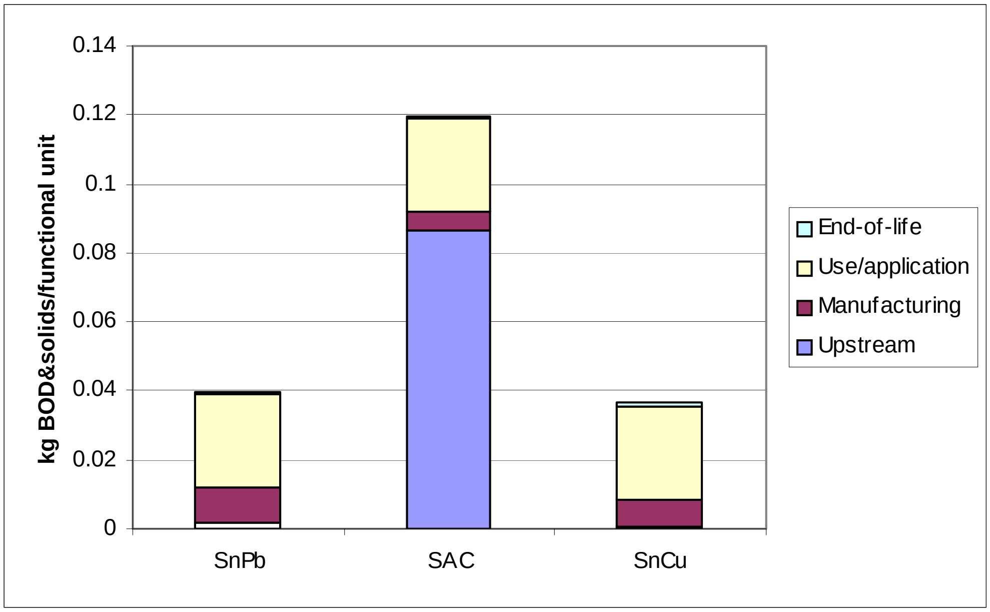


Figure 3-24. Bar Solder Total Life-Cycle Impacts: Water Quality (BOD & Solids)

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

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

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

Water Quality Impacts by Process Group (Bar Solder)

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

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

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

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

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

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

Top Contributors to Water Quality Impacts (Bar Solder)

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

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

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

3.2.10.4 Limitations and uncertainties

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

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

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

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

3.2.11 Occupational Human Health Impacts

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

3.2.11.1 Characterization

Potential Human Health Impacts

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

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

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

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

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

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

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

Occupational Human Health Characterization: Non-Cancer

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

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

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

where:

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

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

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

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

where:

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

Occupational Human Health Characterization: Cancer

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

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

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

where:

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

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

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

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

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

N/A=not applicable

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

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

where:

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

3.2.11.2 Paste solder results

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

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

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

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

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

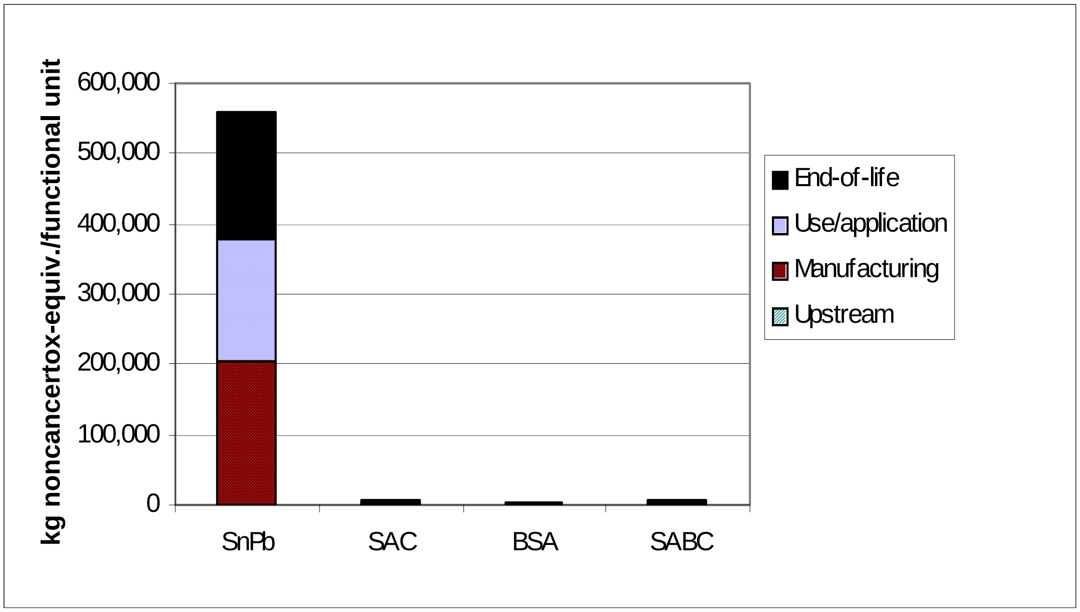


Figure 3-25. Solder Paste Total Life-Cycle Impacts: Occupational Non-Cancer

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

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

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

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

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

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

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

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

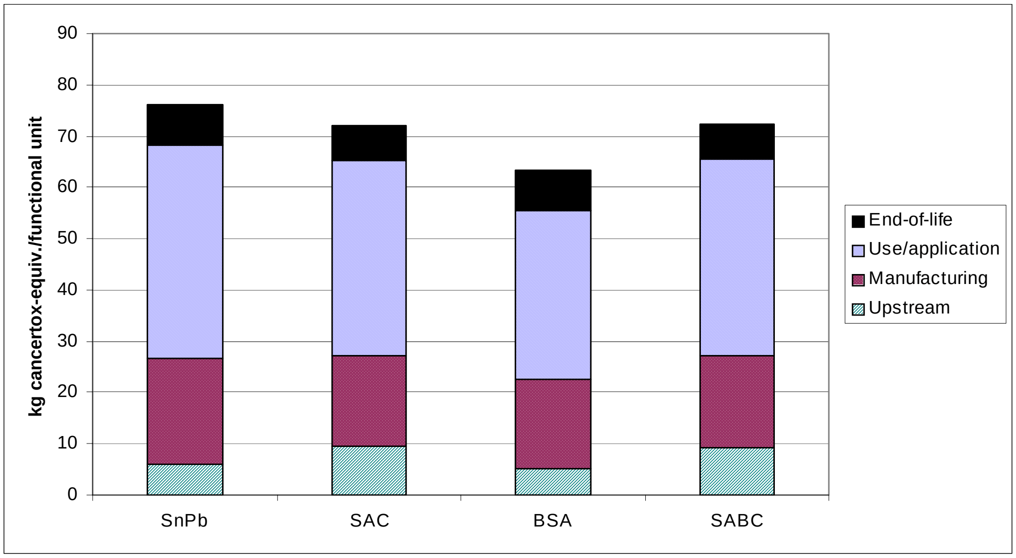


Figure 3-26. Solder Paste Total Life-Cycle Impacts: Occupational Cancer

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

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

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

Occupational Impacts by Process Group (Paste Solder)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Top Contributors to Occupational Impacts (Paste Solder)

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

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

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

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

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

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

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

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

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

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

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

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

3.2.11.3 Bar solder results

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

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

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

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

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

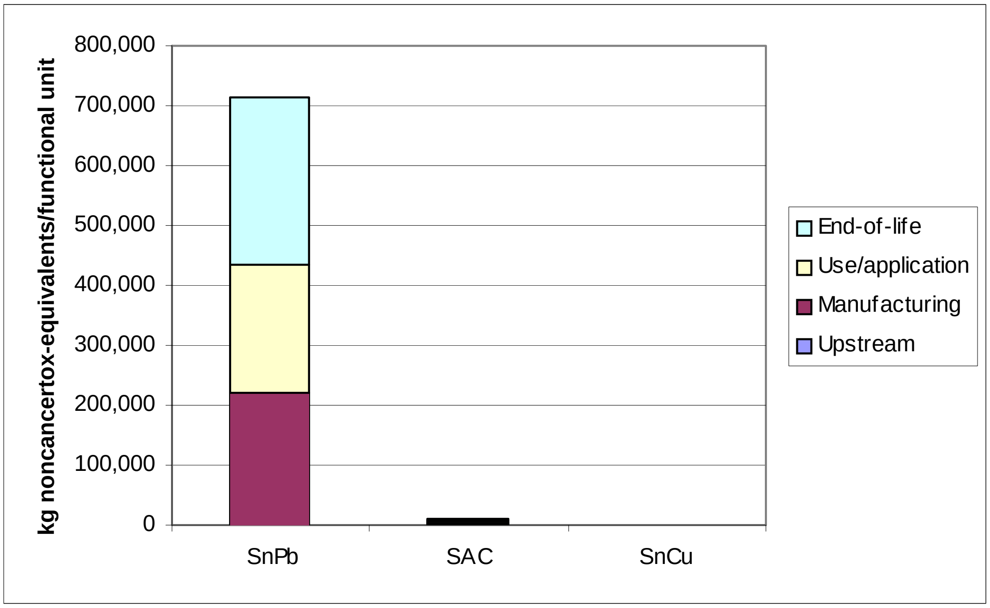


Figure 3-27. Bar Solder Total Life-Cycle Impacts: Occupational Non-Cancer

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

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

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

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

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

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

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

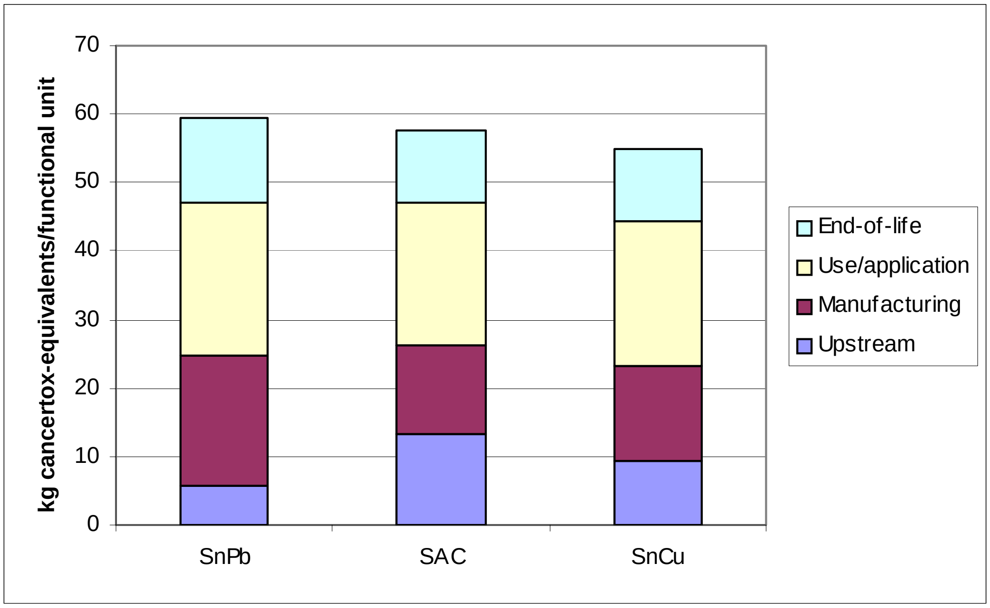


Figure 3-28. Bar Solder Total Life-Cycle Impacts: Occupational Cancer

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

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

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

Occupational Impacts by Process Group (Bar Solder)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Top Contributors to Occupational Impacts (Bar Solder)

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

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

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

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

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

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

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

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

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

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

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

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

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

3.2.11.4 Limitations and uncertainties

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

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

Each of these is discussed below:

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

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

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

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

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

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

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

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

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

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

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

3.2.12 Public Human Health Impacts

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

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

3.2.12.1 Characterization

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

Public Human Health Characterization: Non-Cancer

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

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

where:

$IS_{CHP\text{-}NC}$ equals the impact score for chronic non-cancer effects to the public for chemical *i* (kg non-cancertox-equivalent) per functional unit;

HV_{NC} equals the hazard value for chronic non-cancer effects for chemical *i* (based on either inhalation or oral toxicity, see Section 3.2.11.1); and

$Amt_{TC\ output}$ equals the amount of toxic inventory output of chemical *i* to air, water, and soil (kg) per functional unit.

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

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

Public Human Health Characterization: Cancer

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

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

where:

$IS_{CHP\text{-}CA}$ equals the impact score for chronic cancer health effects to the public for chemical *i* (kg cancertox-equivalent) per functional unit;

HV_{CA} equals the hazard value for carcinogenicity for chemical *i* (based on either inhalation or oral carcinogenicity, see Section 3.2.11.1); and

$Amt_{TC\ output}$ equals the amount of toxic inventory output of chemical *i* to air, water, and soil (kg) per functional unit.

3.2.12.2 Paste solder results

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

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

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

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

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

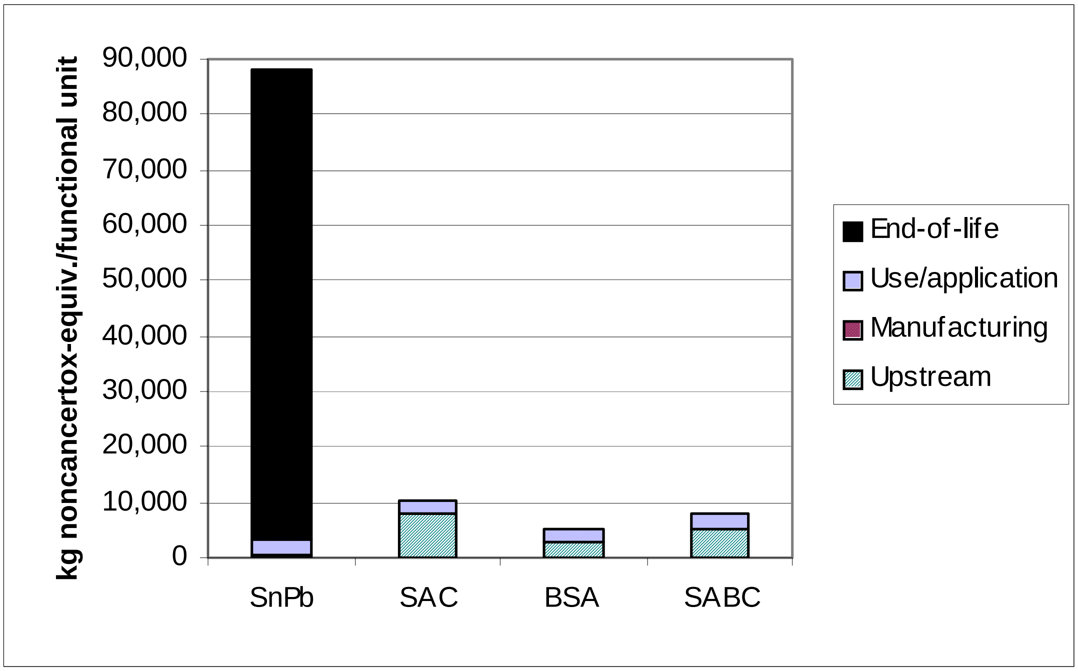

Figure 3-29. Solder Paste Total Life-Cycle Impacts: Public Non-Cancer

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

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

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

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

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

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

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

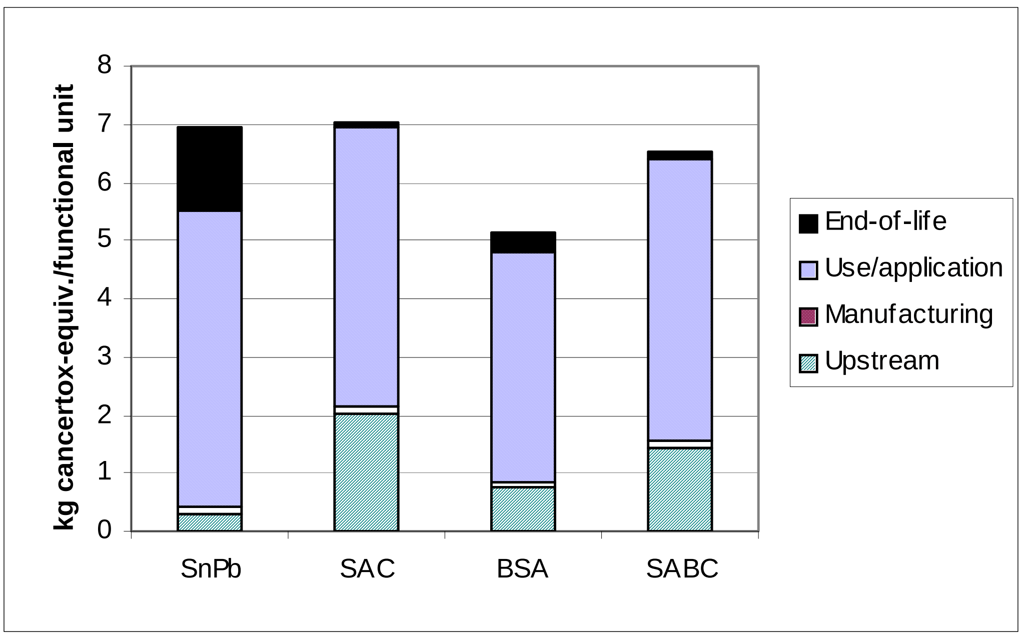

Figure 3-30. Solder Paste Total Life-Cycle Impacts: Public Cancer

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

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

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

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

Public Health Impacts by Process Group (Paste Solder)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Top Contributors to Public Health Impacts (Paste Solder)

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

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

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

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

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

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

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

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

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

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

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

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

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

* Flux names have been removed to protect confidentiality.

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

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

3.2.12.3 Bar solder results

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

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

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

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

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

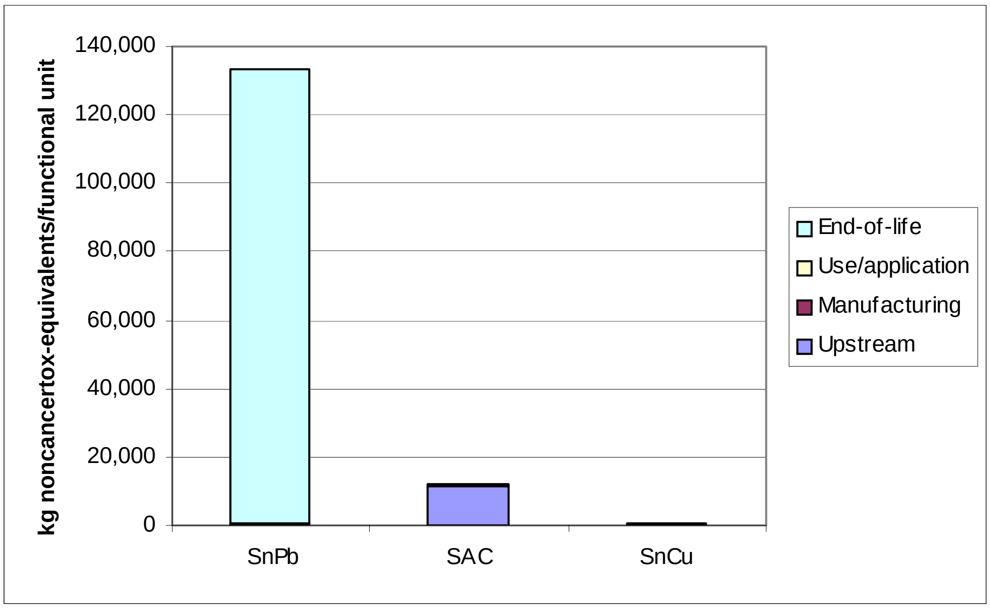

Figure 3-31. Bar Solder Total Life-Cycle Impacts: Public Non-Cancer

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

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

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

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

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

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

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

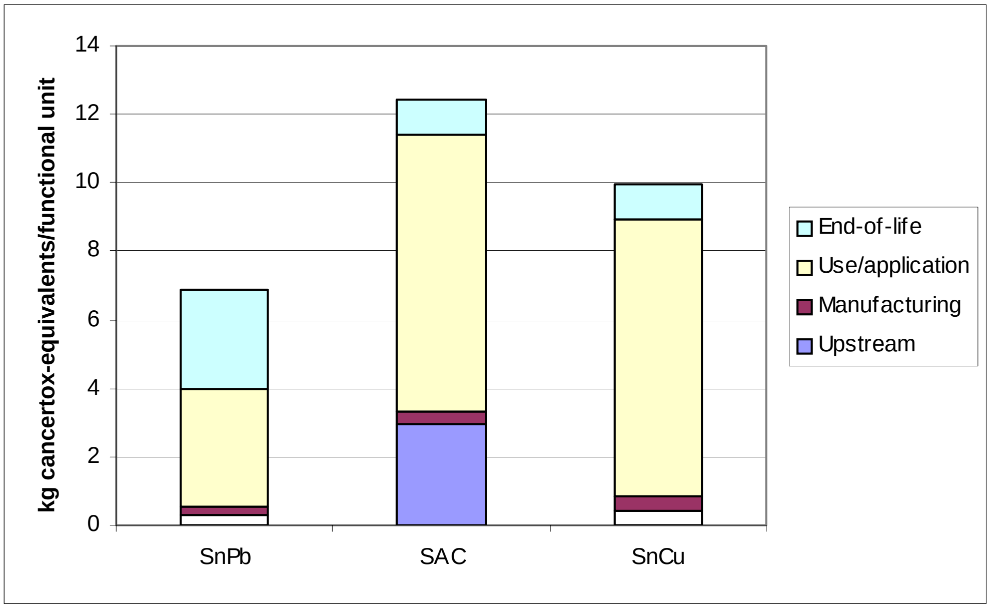

Figure 3-32. Bar Solder Total Life-Cycle Impacts: Public Cancer

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

Public Health Impacts by Process Group (Bar Solder)

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

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

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

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

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

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

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

Table 3-93. Public non-cancer impacts by life-cycle stage and process group (bar solder)

Life-cycle stage	SnPb		SAC		SnCu	
Process group	Score*	%	Score*	%	Score*	%
UPSTREAM						
Sn production	1.29E+02	0.0964	2.74E+02	2.24	2.11E+02	28.8
Pb production	5.52E+01	0.0412	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	1.13E+04	92.4	N/A	N/A
Cu production	N/A	N/A	9.13E+00	0.0749	8.96E+00	1.22
Total	**1.84E+02**	**0.138**	**1.16E+04**	**94.7**	**2.20E+02**	**30.3**
MANUFACTURING						
Solder manufacturing	7.63E+00	0.0057	9.67E+00	0.0792	9.58E+00	1.31
Post-industrial recycling	4.52E+01	0.0337	9.88E+00	0.0809	1.69E+01	2.31
Total	**5.28E+01**	**0.0394**	**1.95E+01**	**0.160**	**2.65E+01**	**3.62**
USE/APPLICATION						
Solder application	4.55E+02	0.339	4.65E+02	3.81	4.65E+02	63.4
Total	**4.55E+02**	**0.339**	**4.65E+02**	**3.81**	**4.65E+02**	**63.4**
END-OF-LIFE						
Landfill	7.10E+04	53.5	1.01E+00	0.0082	2.32E-02	0.0032
Incineration	1.80E+04	13.4	-6.70E-02	-0.0005	-3.17E-01	-0.0433
Demanufacture	3.12E-01	0.0002	2.73E-01	0.0022	2.71E-01	0.0370
Cu smelting	5.50E+00	0.0041	1.99E+00	0.0163	1.97E+01	2.68
Unregulated	4.37E+04	32.6	1.63E+02	1.34	1.93E+00	0.264
Total	**1.33E+05**	**99.5**	**1.66E+02**	**1.36**	**2.16E+01**	**2.94**
GRAND TOTAL	**1.34E+05**	**100**	**1.22E+04**	**100**	**7.33E+02**	**100**

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

Potential upstream impacts arise from outputs of potentially carcinogenic materials in the extraction and processing of the various metals present in the alloys. With the bar solder alloys, the public cancer impact scores from tin extraction and processing comprise between about 3.7 and 4.2 percent of the total; for SnPb, about 0.48 percent of impacts are from lead extraction and processing; and for SnCu about 0.0086 percent for copper extraction and processing. For SAC, silver production dominates upstream impacts, contributing about 19 percent to the total score. Public cancer impacts from silver processing exceed impacts from tin processing in solders that contain both metals, even though the silver content of the alloys is much less than the tin content. As described in earlier sections, SAC is 95.5 percent tin and only 3.9 percent silver, yet its impacts from silver production are greater than those from tin production. This indicates that potential cancer impacts from silver extraction and processing outputs are disproportionately high compared to the other solder metals.

In the manufacturing life-cycle stage of SnPb, post-industrial recycling contributes slightly more to total impacts than does solder manufacturing. For the lead-free alloys, solder manufacturing contributes more than does post-industrial recycling. SAC solder manufacturing contributes 2.7 percent compared to SAC post-industrial recycling, which contributes 0.49

percent. SnCu solder manufacturing contributes about 3.3 percent compared to about 1.1 percent for post-industrial recycling. This is because there is more recycled metal content in SnPb than for SAC and SnCu.

Table 3-94. Public cancer impacts by life-cycle stage and process group (bar solder)

Life-cycle stage	**SnPb**		**SAC**		**SnCu**	
Process group	Score*	%	Score*	%	Score*	%
UPSTREAM						
Sn production	2.55E-01	3.72	5.40E-01	4.35	4.17E-01	4.19
Pb production	3.31E-02	0.483	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	2.41E+00	19.3	N/A	N/A
Cu production	N/A	N/A	8.76E-04	0.0070	8.60E-04	0.0086
Total	**2.88E-01**	**4.20**	**2.95E+00**	**23.7**	**4.18E-01**	**4.20**
MANUFACTURING						
Solder manufacturing	1.14E-01	1.67	3.30E-01	2.66	3.28E-01	3.29
Post-industrial recycling	1.51E-01	2.20	6.08E-02	0.489	1.04E-01	1.05
Total	**2.66E-01**	**3.87**	**3.91E-01**	**3.15**	**4.32E-01**	**4.34**
USE/APPLICATION						
Solder application	3.41E+00	49.7	8.08E+00	65.0	8.07E+00	81.0
Total	**3.41E+00**	**49.7**	**8.08E+00**	**65.0**	**8.07E+00**	**81.0**
END-OF-LIFE						
Landfill	1.15E+00	16.7	5.41E-04	0.0044	5.65E-04	0.0057
Incineration	2.96E-01	4.31	1.12E-02	0.0903	1.16E-02	0.117
Demanufacture	4.70E-04	0.0068	4.11E-04	0.0033	4.08E-04	0.0041
Cu smelting	1.37E-02	0.199	1.19E-02	0.0958	1.18E-02	0.119
Unregulated	1.44E+00	21.0	9.87E-01	7.94	1.02E+00	10.2
Total	**2.90E+00**	**42.3**	**1.01E+00**	**8.13**	**1.04E+00**	**10.5**
GRAND TOTAL	**6.87E+00**	**100**	**1.24E+01**	**100**	**9.96E+00**	**100**

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

Top Contributors to Public Health Impacts (Bar Solder)

Table 3-95 presents the specific materials or flows contributing greater than 1 percent of public *non-cancer* impacts by bar solder. As presented above, the SnPb impacts are dominated by the EOL stage. In particular, lead emissions to water, from both landfilling and incineration at EOL constitute about 66 percent of the total SnPb life-cycle impacts combined. For both of these processes, lead emissions to water occur from landfill leachate (i.e., from leaching of waste electronics or incinerator ash). Lead emissions to air, soil, and water from unregulated recycling and disposal are the next greatest contributors (12, 12, and 8.2 percent, respectively); these are from direct releases to the environment.

Table 3-95. Top contributors to public non-cancer impacts (bar solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	End-of-life	Solder landfilling (SnPb)	Lead to water	53.3
	End-of-life	Solder incineration (SnPb)	Lead to water	13.1
	End-of-life	Unregulated recycling and disposal (SnPb)	Lead to air	12.3
	End-of-life	Unregulated recycling and disposal (SnPb)	Lead to soil	12.3
	End-of-life	Unregulated recycling and disposal (SnPb)	Lead to water	8.19
SAC	Upstream	Silver production	Sulphur dioxide to air	49.6
	Upstream	Silver production	Lead to soil	36.5
	Use/application	Electricity generation	Sulphur dioxide to air	3.68
	Upstream	Silver production	Lead to air	2.63
	Upstream	Tin production	Sulphur dioxide to air	2.24
	Upstream	Silver production	Arsenic to soil	1.43
	End-of-life	Unregulated recycling and disposal (SAC)	Silver to water	1.32
SnCu	Use/application	Electricity generation	Sulphur dioxide to air	61.9
	Upstream	Tin production	Sulphur dioxide to air	29.1
	Manufacturing	Electricity generation for post-industrial recycling	Sulphur dioxide to air	2.19
	End-of-life	Post-consumer copper smelting (SnCu)	Copper to air	1.20
	End-of-life	Post-consumer copper smelting (SnCu)	Copper to soil	1.20
	Upstream	Copper production	Sulphur dioxide to air	1.18
	Manufacturing	Electricity generation for solder manufacturing	Sulphur dioxide to air	1.09

While the SnPb public health non-cancer impacts are dominated by EOL lead emissions, SAC is largely influenced by upstream metals production processes. Specific flows that contribute greatly to the SAC impact scores include sulphur dioxide from silver production (50 percent contribution) and lead emissions to soil from silver production (about 37 percent). Smaller contributors are sulphur dioxide from electricity generation for wave soldering, lead emissions to air from silver production, sulphur dioxide emissions from tin production, arsenic emissions to soil from silver production, and silver emissions to water from unregulated recycling and disposal.

Sulphur dioxide emissions from electricity generation in the use/application stage are the top contributor to SnCu public non-cancer impacts at about 62 percent, followed by sulphur dioxide emissions to air from tin production at 29 percent. Other top contributors are sulphur dioxide and copper to air from various processes in a mix of life-cycle stages.

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

The public non-cancer impact scores of the lead-free bar solders, on the other hand, are dominated somewhat by sulphur dioxide emissions (HV=660), and to a lesser extent (for SAC), by lead emissions from silver production. The results suggest that sulphur dioxide, which has a lower HV than silver's 10,000 HV, has a greater inventory amount than silver, and that the metals in the lead-free solders are either not of a high enough toxicity or not enough quantity to exceed the impacts from sulphur dioxide. The relatively high percent contributions of lead emissions from silver production to the total impacts of SAC are primarily due to lead's high HV, rather than a large inventory amount.

Table 3-96 presents the specific materials or flows contributing at least 1 percent of public *cancer* impacts by bar solder. The top contributor to public cancer impacts for each bar alloy is flux from wave application in the use/application stage. For the SnPb bar solder alloy, flux material "F" contributes approximately 26 percent of total public impact score. (Note, letters are used in place of flux chemical names to protect confidentiality of companies that supplied the data.) The second greatest contributor to SnPb impacts are lead outputs to water from landfilling that contribute 17 percent to total public cancer impacts. The relatively high impact score for this flow is due to the fact that lead was found to leach substantially more than the metals in the other alloys (see Chapter 2 and Appendix C). Flux E from the wave application is the third greatest contributor to SnPb cancer impacts at 15 percent. The remaining top contributors for SnPb shown in Table 3-86 include several different flows, all of which contribute approximately 7 percent or less. These include tin to water, nitrogen oxides to air, lead to air and soil, methane to air, and dust to air. These emissions are from various processes and life-cycle stages as shown in the table.

Table 3-96. Top contributors to public cancer impacts (bar solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	Use/application	SnPb (bar) wave application	Flux material F *	25.5
	End-of-life	Solder landfilling (SnPb)	Lead to water	17.2
	Use/application	SnPb (bar) wave application	Flux material E *	15.3
	End-of-life	Unregulated recycling and disposal (SnPb)	Tin to air	6.68
	Use/application	Electricity generation	Nitrogen oxides to air	5.36
	End-of-life	Unregulated recycling and disposal (SnPb)	Tin to water	4.45
	End-of-life	Solder incineration (SnPb)	Lead to water	4.18
	End-of-life	Unregulated recycling and disposal (SnPb)	Lead to air	3.92
	End-of-life	Unregulated recycling and disposal (SnPb)	Lead to soil	3.92
	End-of-life	Unregulated recycling and disposal (SnPb)	Lead to water	2.62
	Use/application	Electricity generation	Methane to air	2.39
	Upstream	Tin production	Nitrogen oxides to air	2.18
	Upstream	Tin production	Dust (unspecified) to air	1.25
SAC	Use/application	SAC (bar) wave application	Flux material C *	16.9
	Use/application	SAC (bar) wave application	Flux material F *	14.1
	Use/application	SAC (bar) wave application	Flux material D *	14.1
	Upstream	Silver production	Dust (unspecified) to air	10.2
	Use/application	SAC (bar) wave application	Flux material E *	8.46
	Use/application	SAC (bar) wave application	Flux material A *	5.66
	End-of-life	Unregulated recycling and disposal (SnAgCu)	Tin to air	4.90

Table 3-96. Top contributors to public cancer impacts (bar solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
	End-of-life	Unregulated recycling and disposal (SnAgCu)	Tin to water	3.27
	Use/application	Electricity generation	Nitrogen oxides to air	3.00
	Upstream	Tin production	Nitrogen oxides to air	2.56
	Upstream	Silver production	Arsenic to soil	2.42
	Upstream	Silver production	Methane to air	2.07
	Use/application	SAC (bar) wave application	Flux material B *	1.94
	Upstream	Silver production	Nitrogen oxides to air	1.74
	Upstream	Tin production	Dust (unspecified) to air	1.47
	Use/application	Electricity generation	Methane to air	1.34
	Upstream	Silver production	Arsenic to air	1.17
SnCu	Use/application	SnCu (bar) wave application	Flux material C *	21.3
	Use/application	SnCu (bar) wave application	Flux material D *	17.7
	Use/application	SnCu (bar) wave application	Flux material F *	17.7
	Use/application	SnCu (bar) wave application	Flux material E *	10.7
	Use/application	SnCu (bar) wave application	Flux material A *	7.08
	End-of-life	Unregulated recycling and disposal (SnCu)	Tin to air	6.38
	End-of-life	Unregulated recycling and disposal (SnCu)	Tin to water	4.25
	Use/application	Electricity generation	Nitrogen oxides to air	3.78
	Upstream	Tin production	Nitrogen oxides to air	2.49
	Use/application	SnCu (bar) wave application	Flux material B *	2.43
	Use/application	Electricity generation	Methane to air	1.68
	Upstream	Tin production	Dust (unspecified) to air	1.43

* Flux names have been removed to protect confidentiality.

The top three contributors to bar SAC cancer impacts are three fluxes from wave application that, when combined, constitute about 45 percent of the total public cancer impacts for SAC. The fourth top contributor is dust from silver production (10 percent). The remaining top contributors each contribute 8 percent or less. The top five contributors to bar SnCu cancer impacts are fluxes from wave application, which combined constitute 74 percent of total impacts. The remaining individual contributors contribute 6 percent or less, and are from various processes and life-cycle stages as shown in the table.

Arsenic is the only top material contributor to the public cancer impacts that is a known human carcinogen (cancer HV=29). The only other material that has been classified by EPA or IARC as to carcinogenicity is lead, which is a probable human carcinogen. As discussed previously, the LFSP LCIA methodology assigns chemicals with a positive WOE classification, but no slope factor, a HV equal to 1, which is representative of an average HV. The methodology also assigns chemicals with no cancer toxicity data a HV of 1 to avoid the bias that typically favors chemicals with missing data. This was the case with all of the other top contributors to solder paste public cancer impacts, which were all assigned a HV of 1 due to missing data; therefore, much of the public cancer impacts are driven by a lack of data, rather than known carcinogenic hazards. This is particularly true for the lead-free alloys, which are not affected by lead emissions. For SnPb, on the other hand, of the top contributors in Table 3-96, lead outputs contribute about 32 percent to the total impacts (for landfilling, incineration, and unregulated recycling/disposal combined), and the lead HV is based on some carcinogenic rating, although the potential potency of lead as a carcinogen is not known; therefore, SnPb is *less* driven by a lack of data than the lead-free alloys. It is still highly driven by a lack of data given that all of the remaining top contributors, aside from lead emissions, have no applicable carcinogenic data.

3.2.12.4 Limitations and uncertainties

This section summarizes the limitations and uncertainties associated with public non-cancer and cancer health impacts. The public health LCIA limitations and uncertainties that address (1) structural or modeling limitations and (2) toxicity data limitations, are identical to those for occupational health impacts. For a detailed discussion, refer to Section 3.2.11.4. For example, much of the public *cancer* impact results are driven by a lack of toxicity data, rather than known carcinogenic hazards. In addition, the LCI data limitations for public health impacts in many cases are similar to those described in Section 3.2.11.4. LCI data limitations pertinent to public health impacts are summarized below.

For SnPb, the EOL impacts dominate non-cancer total impacts for both paste and bar solder results, and cancer impacts also are somewhat influenced by EOL. The limitations and uncertainties for SnPb are most influenced by the EOL uncertainties and limitations. Public health impacts are based on process outputs as opposed to occupational impacts that are based on process inputs. The EOL outputs have uncertainties associated with the inventory quantities as they were based on assumptions about partitioning of the metals to various media, depending on the EOL process. Details of the limitations and uncertainties for outputs from each of the EOL processes are presented in Chapter 2, which provides limitations and uncertainties in the EOL inventory.

To summarize, for landfilling there is relatively low uncertainty associated with the leachability testing data used to calculate metal outputs from the landfill process, which are primary data collected for the purposes of the LFSP. Uncertainties do exist and are associated with (1) the TCLP test method itself and its representativeness of actual landfill conditions, and (2) the analytical method (for example, limitations in analytical detection limits and quality uncertainties associated with laboratory blanks). These limitations and uncertainties are discussed in more detail in Chapter 2, which summarizes the leachability results, and in Appendix C, which presents the leachability report. To address concerns that the TCLP test method is not representative of actual landfill conditions (i.e., it overstates the leachability of lead), a bounding analysis has been conducted that uses a lower bound of lead leachability to help determine the sensitivity of the results to the leachability data (see Section 3.3).

For incineration, secondary literature was reviewed to make assumptions about metal releases and partitioning to various environmental media. This introduced slightly more uncertainty into the incineration outputs than is expected with the landfilling data. Uncertainties associated with unregulated recycling and disposal are due to the almost complete absence of analytical data on the partitioning of metals among environmental media for these processes. EPA is currently conducting trials to assess metal emissions from open burning of electronics waste. These data could be used later to reassess the assumptions used here for unregulated recycling and disposal processes.

Uncertainties from copper smelting have less effect on the results as this process contributes small proportions to the total impacts. Nonetheless, uncertainties associated with copper smelting arise from the inability of the researchers to get direct quantitative data from primary data sources. Conversations with primary data suppliers and literature reviews, led to assumptions that are believed to be reasonable to predict outputs; therefore, uncertainty is considered to be acceptable for copper smelting outputs.

In addition to metal output uncertainties, there are EOL uncertainties related to the assumptions about EOL dispositions (e.g., 72 percent of solder goes directly to landfilling for SnPb, SAC, SABC, and SnCu). These are discussed in greater detail in Chapter 2.

Public health impacts of the lead-free alloys are generally dominated by the upstream and use/application life-cycle stages. The uncertainties associated with these stages affect the uncertainties for these alloys more so than the EOL uncertainties discussed above. Upstream uncertainties stem from the use of secondary data sources. Silver production, which accounts for a large proportion of the total public non-cancer impacts for the silver-bearing solders, has associated uncertainties that are described in Section 3.2.1.4. As presented in that section, although the secondary silver data set are considered "good" by GaBi, an alternate silver inventory (from DEAM) is used to assess the sensitivity of LCIA results to silver production data (see Section 3.3).

The use/application limitations and uncertainties related to electricity generation for paste reflow soldering outputs arise from two issues: (1) electricity generation outputs are based on the amount of electrical power used in the reflow solder process that was determined based on two primary data points for reflow energy covering a large range in energy, and (2) electricity production data are from a secondary source. Electricity consumption in the use/application stage is evaluated in a sensitivity analysis for paste results (see Section 3.3). For a more detailed discussion, refer to Section 3.2.1.4. Uncertainties from electricity use during bar solder wave application relate to the use of secondary electricity generation data, but the reflow energy uncertainty mentioned above does not apply.

Other uncertainties related to wave and reflow application relate to the assumption that all the flux materials, either in the paste or as applied during wave soldering, are volatilized and released to the environment. Primary data were not available on the capture of these materials or on the actual releases to the environment; therefore, the assumption that all the flux materials are released into the environment is an upper bound estimate for flux emissions to air, and a source of uncertainty in the application processes. This is mostly relevant to the human health cancer impacts for bar solders, each of which have a flux as their highest top contributor to total cancer impacts.

Given that the lead toxicity is such an important driver of public non-cancer impacts, further investigation into the impact score results has been done. For non-cancer impacts, the LCIA methodology employed in this study calculates HVs based on either inhalation or oral NOAELs or LOAELs. For chemicals that do not have NOAELs, LOAELs are used as the basis of the toxicity hazard value. If a chemical has both an inhalation and oral NOAEL, the toxicity value that results in the higher toxicity is chosen. This is a simple screening methodology that allows for many chemicals through various transport and exposure pathways to be considered in an analysis. The disadvantage of such a screening method is that it is applied to a variety of chemicals with various potential exposure scenarios (as is the case in an LCA), and the actual toxicity and exposure for any one particular chemical in a particular process may not be accurately represented. This method simply identifies chemicals of concern based on the most toxic exposure pathway for that chemical without regard to the specific pathway in a particular process. The reason this method uses either inhalation or oral toxicity data is because it is far too cumbersome to select a particular route of exposure for every chemical in every process in the life-cycle analysis; however, given that the lead toxicity is such an important driver of public non-cancer health impacts, further understanding and resolution of the data is warranted.

The lead non-cancer HV in the LCIA methodology employed in this study is based on an *inhalation* LOAEL. Of the top contributors in Table 3-95 and Table 3-96, 93 percent of the paste results and 75 percent of the bar results were from lead emissions to *water*. To identify what the results might look like if an *oral* NOAEL were used, an alternate analysis is presented here. Note, however, that this is not consistent with the methodology employed throughout all the life-cycle stages, which uses the most toxic NOAEL or LOAEL, regardless of the route of exposure. While an oral NOAEL might represent a more accurate exposure pathway for most of the EOL releases, it may not do so for other processes represented in the analysis. Because lead released to water is a large proportion of impacts, it seems worthy to estimate the sensitivity of the results to the inhalation NOAEL by conducting the analysis with an oral NOAEL for lead.

In the baseline case, the non-cancer HV for lead is 62,427, which is based on an inhalation LOAEL of 0.011 mg/m^3 (ATSDR, 1999), which is calculated to be equivalent to a NOAEL of 0.0011 mg/m^3. In the alternative case, the non-cancer HV is 10,000, based on an oral NOAEL of 0.0015 mg/kg-day (ATSDR, 1999). The HVs are calculated using equations presented in Section 3.2.11.1. Figures 3-33 and 3-34 show the comparative results for the non-cancer impacts using different lead toxicity non-cancer HVs for both the paste and bar solders, respectively. The results from the alternate analysis, which is based on the oral NOAEL, have the same conclusions for both the paste and bar analyses as they had for the baseline analyses; that is, SnPb remains the highest impact score, by a much smaller margin for the alternative analysis compared to the baseline. For the paste results, SnPb impacts were 7.6 times greater than SAC in the baseline case, and SnPb was 2.1 times greater than SAC in the alternative case. In both cases, EOL remained the top contributor, but to a lesser degree in the alternate case. In the baseline case, EOL contributed 96 percent to total impacts. With the oral-based HV, EOL comprised 82 percent of the total impacts.

For bar solder results, SnPb was 10.9 times greater than SAC in the baseline case (inhalation-based HV) and 2.7 times greater than SAC in the alternate case. In the baseline, EOL contributed 99 percent to total impacts, and in the alternate case, EOL contributed 97 percent to total impacts.

It is important to reiterate that by changing only the lead HV, we are not being consistent in how other chemicals are treated; therefore, this analysis should *not* be construed as a reasonable analysis to replace the baseline analysis. It is simply conducted to determine how the results are impacted given a change in only the lead non-cancer HV.

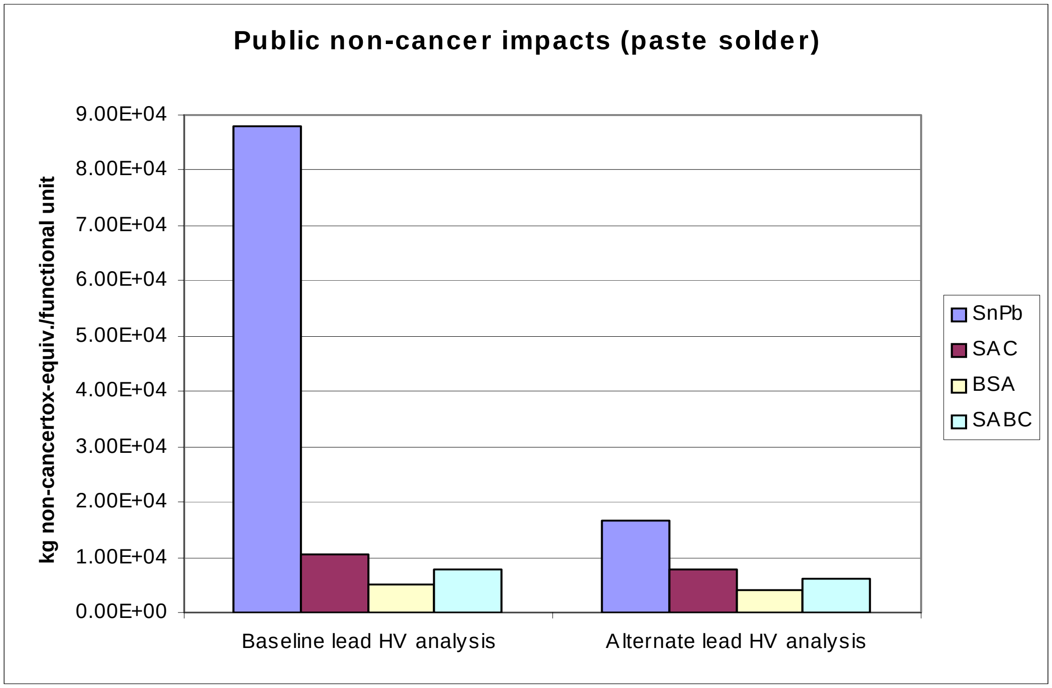

Figure 3-33. Comparative lead HV analysis (paste solder)

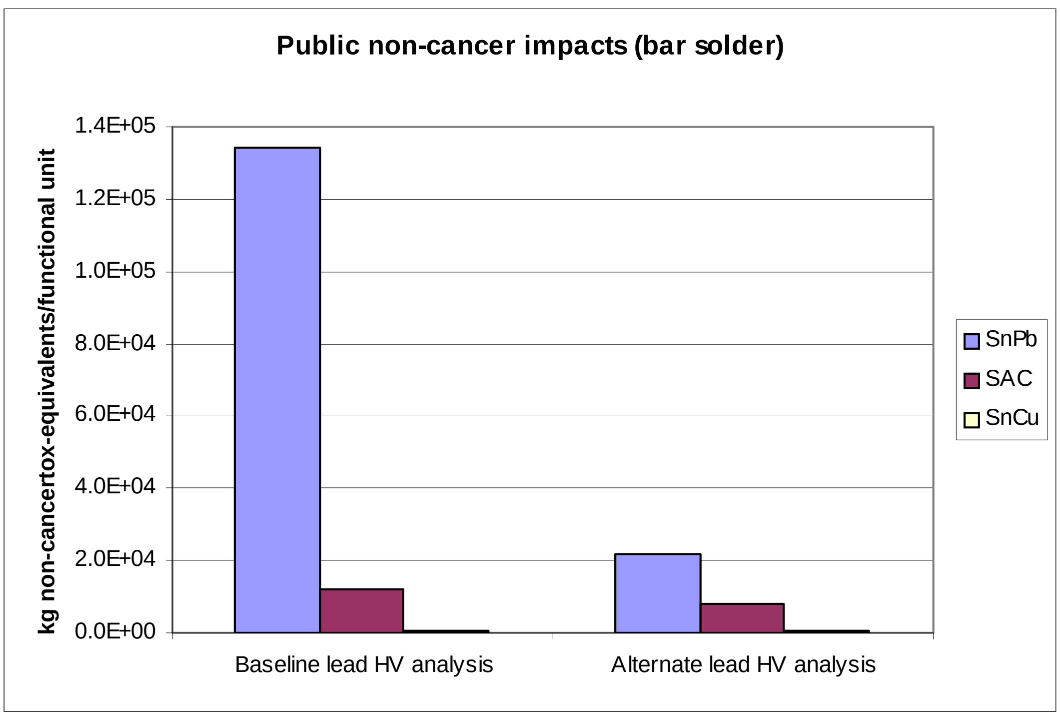

Figure 3-34. Comparative lead HV analysis (bar solder)

3.2.13 Aquatic Ecotoxicity Impacts

3.2.13.1 Characterization

Ecotoxicity refers to effects of chemical outputs on non-human living organisms. Impact categories could include both ecotoxicity impacts to aquatic and terrestrial ecosystems. The method for calculating terrestrial toxicity, however, would be the same as for the chronic, non-cancer public toxicity impacts described above, which are based on mammalian toxicity data. As the relative ranking approach of the LCIA toxicity method does not modify the toxicity data for different species or for fate and transport, both human and terrestrial LCIA impacts are the same; therefore, only aquatic toxicity, which uses a different methodology, is presented below.

Toxicity measures for fish are used to represent potential adverse effects to organisms living in the aquatic environment from exposure to a toxic chemical. Impact scores are based on the identity and amount of toxic chemicals as outputs to surface water. Impact characterization is based on CHEMS-1 acute and chronic hazard values for fish (Swanson *et al.*, 1997) combined with the inventory amount. Both acute and chronic impacts comprise the aquatic ecotoxicity term. The HVs for acute and chronic toxicity are based on LC_{50} (the lethal concentration to 50 percent of the exposed fish population) and NOEL (no-observed-effect level) (or NOEC [no-observed-effect concentration]) toxicity data, respectively, mostly from toxicity tests in fathead minnows (*Pimephales promelas*) (Swanson *et al.*, 1997). The acute fish HV is calculated by:

$$(HV_{FA})_i = \frac{1/(LC_{50})_i}{1/(LC_{50})_{mean}}$$

where:

HV_{FA}	equals the hazard value for acute fish toxicity for chemical *i* (unitless);
LC_{50}	equals the lethal concentration to 50 percent of the exposed fish population for chemical *i*; and
$LC_{50\ mean}$	equals the geometric mean LC_{50} of available fish LC_{50} values in Appendix E (24.6 mg/L).

The chronic fish HV is calculated by:

$$(HV_{FC})_i = \frac{1/NOEL_i}{1/NOEL_{mean}}$$

where:

HV_{FC} equals the hazard value for chronic fish toxicity for chemical *i*;

NOEL equals the no-observed-effect level for fish for chemical *i*; and

$NOEL_{mean}$ equals the geometric mean NOEL of available fish NOEL values in Appendix D (3.9 mg/L).

For chemicals that do not have chronic fish toxicity data available, but do have LC_{50} data, the LC_{50} and the log K_{ow} of the chemical are used to estimate the NOEL. Based on studies comparing the LC_{50} to the NOEL (Kenega, 1982; Jones and Schultz, 1995, and Call *et al.*, 1985) as reported in Swanson *et al.* (1997), NOEL values for organic chemicals within a certain range of log K_{ow} values are calculated using the following continuous linear function:

For organics with 2 # log K_{ow} < 5:

$$NOEL = LC_{50}/(5.3 \, x \log K_{ow} - 6.6)$$

Organic chemicals with high log K_{ow} values (i.e., greater than 5) are generally more toxic to fish and are not expected to follow a continuous linear function with K_{ow}, thus, they are estimated directly from the LC_{50}. In addition, inorganic chemicals are poorly fat soluble and their fish toxicity does not correlate to log K_{ow}. The NOEL values of the inorganic chemicals were, therefore, also based on the fish LC_{50} values.

For inorganics or organics with log K_{ow} $5:

$$NOEL = 0.05 \, x \, (LC_{50})$$

For organics with log K_{ow}<2, which are poorly fat soluble but assumed to have a higher NOEL value than those with higher K_{ow} values or than inorganics, the NOEL is estimated as follows:

For organics with log K_{ow} <2:

$$NOEL = 0.25 \, x \, (LC_{50})$$

Once the HVs are calculated, whether from NOEL data or estimated from the LC_{50} and the K_{ow}, the aquatic toxicity impact score is calculated as follows:

$$(IS_{AQ})_i = [(HV_{FA} + HV_{FC}) \, x \, Amt_{TCoutput,water}]_i$$

where:

IS_{AQ} equals the impact score for aquatic ecotoxicity for chemical *i* (kg aquatictox-equivalent) per functional unit;

HV_{FA} equals the hazard value for acute fish toxicity for chemical *i* (unitless);

HV_{FC} equals the hazard value for chronic fish toxicity for chemical *i*; and,

$Amt_{TC\ output,water}$ equals the toxic inventory output amount of chemical *i* to water (kg) per functional unit.

3.2.13.2 Paste solder results

Total Aquatic Ecotoxicity Impacts by Life-Cycle Stage (Paste Solder)

Table 3-97 presents the solder paste results for aquatic ecotoxicity impacts by life-cycle stage, based on the impact assessment methodology presented above. The table lists the aquatic ecotoxicity impact scores per functional unit for the life-cycle stages of each solder paste alloy, as well as the percent contribution of each life-cycle stage to the total impacts. Figure 3-35 presents the results in a stacked bar chart.

Table 3-97. Aquatic ecotoxicity impacts by life-cycle stage (paste solder)

Life-cycle stage	**SnPb**		**SAC**		**BSA**		**SABC**	
	Score*	%	Score*	%	Score*	%	Score*	%
Upstream	1.07E-01	0.0084	1.85E+01	50.9	5.96E+00	25.5	1.19E+01	31.0
Manufacturing	1.61E-01	0.0126	5.88E-02	0.162	3.40E-02	0.145	5.90E-02	0.153
Use/application	1.49E+00	0.117	1.40E+00	3.84	1.09E+00	4.68	1.40E+00	3.65
End-of-life	1.27E+03	99.9	1.64E+01	45.1	1.63E+01	69.7	2.51E+01	65.2
Total	**1.27E+03**	**100**	**3.64E+01**	**100**	**2.34E+01**	**100**	**3.85E+01**	**100**

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

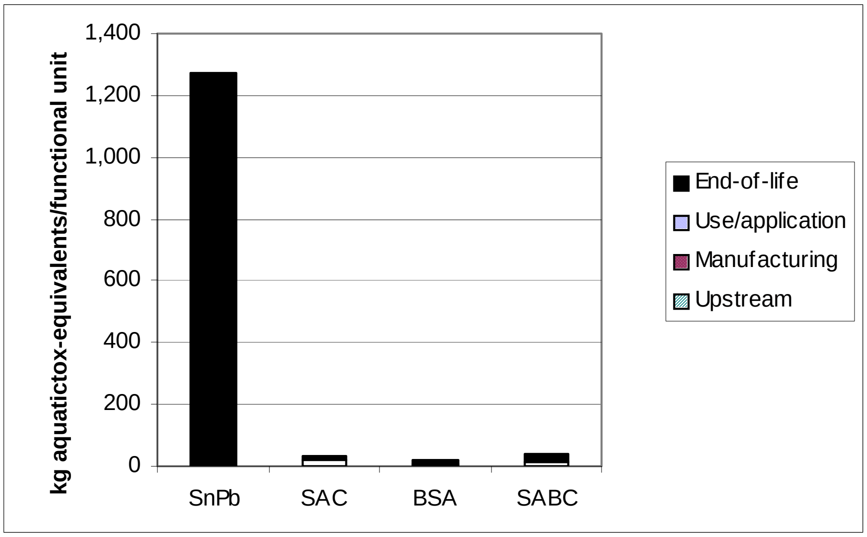

Figure 3-35. Solder Paste Total Life-Cycle Impacts: Aquatic Ecotoxicity

The total aquatic ecotoxicity impact score for SnPb (1,270 kg aquatictox-equivalents/functional unit) is far greater than the other solder paste alloys. SABC has the next greatest impact score (38.5 kg aquatictox-equivalents/functional unit), which is only slightly greater than that of SAC (36.4 kg aquatictox-equivalents/functional unit). BSA has the lowest aquatic ecotoxicity score of all the alloys (23.4 kg aquatictox-equivalents/functional unit).

The EOL stage accounts for nearly all of the SnPb impacts, contributing 99.9 percent to the total aquatic ecotoxicity impact score; however, EOL only accounts for about 45 to 70 percent of total impacts for the lead-free solders. For these alloys, the upstream life-cycle stage also is substantial contributor to total impacts (26 to 51 percent). SAC has the greatest upstream aquatic ecotoxicity impact score at 18.5 kg aquatictox-equivalents/functional unit, which is 51 percent the of total SAC aquatic ecotoxicity impacts. SABC has an upstream aquatic ecotoxicity impact score of 11.9 kg aquatictox-equivalents/functional unit, which contributes 31 percent of SABC's total impacts. BSA has a smaller upstream aquatic ecotoxicity impact score of 5.96 kg aquatictox-equivalents/functional unit, which is 26 percent of BSA's total impacts.

The use/application stage, which is comprised of the reflow soldering process and the associated generation of electricity, is the third greatest contributor for the lead-free alloys. Their aquatic ecotoxicity impact scores from this stage are all relatively small and close to one another in magnitude (1.09, 1.40, and 1.40 kg aquatictox-equivalents/functional unit for BSA, SAC, and SABC, respectively). These scores represent between 3.7 and 4.7 percent of the totals. Of note is that SnPb has a greater impact score for the use/application stage than the lead-free alloys, but the SnPb use/application score only contributes 0.12 percent to SnPb total impacts. This is due to SnPb's high impact score at EOL. Impacts from the manufacturing stage are small, ranging from 0.013 to 0.16 kg aquatictox-equivalents/functional unit for SnPb and BSA, respectively. The manufacturing impacts for each alloy are less than 0.2 percent of total impacts and only 0.01 percent of SnPb impacts.

A benchmark of aquatic ecotoxicity impacts from burning a 60-watt lightbulb is provided here to help put the magnitude of the impacts into perspective. The difference between the SnPb and SAC ecotoxicity results is 1,234 kg aquatictox-equivalents/functional unit. The ecotoxicity impacts associated with burning a 60-watt bulb for one day is 2.48 kg aquatictox-equivalents and for one year is 905 kg aquatictox-equivalents; therefore, the difference between the SnPb and SAC results is equivalent to burning a 60-watt bulb for approximately 1 year and 4 months. On the other hand, the difference between the SAC and BSA results is only 13 kg aquatictox-equivalents/functional unit, which is equivalent to ecotoxicity impacts associated with burning a 60-watt bulb for about 5.2 days.

Aquatic Ecotoxicity Impacts by Process Group (Paste Solder)

Table 3-98 lists the aquatic ecotoxicity impacts of each of the process groups in the life-cycle of the solders. Within the EOL stage of the SnPb life-cycle, landfilling is the greatest contributor to total impacts (78 percent of total aquatic ecotoxicity impacts), followed by incineration (20 percent), and unregulated recycling/disposal (1.2 percent). Copper smelting and demanufacturing are small contributors to the total SnPb aquatic ecotoxicity impacts (0.0034 and 0.00001 percent, respectively).

When evaluating the lead-free alloys alone, unregulated recycling and disposal is the greatest process group contributor to EOL impacts, with scores of 15.0, 14.8, and 22.7 kg aquatictox-equivalents/functional unit for SAC, BSA, and SABC, respectively (which contribute 41 to 63 percent of the total life-cycle impacts depending on the alloy). The second greatest contributor to EOL impacts for the lead-free solders is landfilling (accounting for 3 to 5 percent of total impacts). For the lead-free alloys, unregulated recycling/disposal has far greater aquatic ecotoxicity impacts than landfilling, despite there being more electronics that are presumed to go to landfilling (72 percent) than unregulated disposal (4.5 percent). This is because only a small fraction of each metal in the lead-free alloys (between 0.000013 and 0.024 for all metals) was found to leach during the project's leachability testing (Chapter 2 and Appendix C), but some 12.5 percent (i.e., a fraction of 0.125) of solder metals sent to unregulated recycling and disposal are assumed to be released directly to surface waters via surface water runoff from waste electronics burn piles.

For the lead-free solders, the silver production process is the greatest contributor to upstream aquatic ecotoxicity impacts, contributing 24 to 51 percent to total impacts. For SAC, copper production is the next greatest contributor, followed by tin production, but these contributions are small (0.01 percent or less each). For BSA, after silver production, bismuth production is the next largest contributor at 1.82 percent, followed by tin production at 0.0016 percent contribution. The second greatest contributor for SABC also is bismuth production, however the score is only 0.00645 kg aquatictox-equivalents/functional unit, or 0.015 percent of the total aquatic ecotoxicity impacts. Tin and copper production contribute even less to total impacts (less than 0.008 percent).

The use/application stage has only one process group contributing to that life-cycle stage: solder reflow application; thus, no further discussion on the breakdown of this life-cycle stage is warranted. Although the manufacturing life-cycle stage contributes a small proportion to the overall impacts, Table 3-98 shows the contribution of the two process groups—solder manufacturing and post-industrial recycling—within the manufacturing stage. For all the alloys, post-industrial recycling has a greater aquatic ecotoxicity impact score than the solder manufacturing process group.

Table 3-98. Aquatic ecotoxicity impacts by life-cycle stage and process group (paste solder)

Life-cycle stage	SnPb		SAC		BSA		SABC	
Process group	Score*	%	Score*	%	Score*	%	Score*	%
UPSTREAM								
Sn production	5.06E-04	0.00004	7.41E-04	0.0020	3.79E-04	0.0016	7.48E-04	0.0019
Pb production	1.07E-01	0.0084	N/A	N/A	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	1.85E+01	50.9	5.53E+00	23.6	1.19E+01	31.0
Cu production	N/A	N/A	3.80E-03	0.0104	N/A	N/A	3.18E-03	0.0083
Bi production	N/A	N/A	N/A	N/A	4.26E-01	1.82	6.45E-03	0.0167
Total	**1.07E-01**	**0.0084**	**1.85E+01**	**50.9**	**5.96E+00**	**25.5**	**1.19E+01**	**31.0**
MANUFACTURING								
Solder manufacturing	1.13E-02	0.0009	1.40E-02	0.0386	1.12E-02	0.0480	1.41E-02	0.0366
Post-industrial recycling	1.49E-01	0.0117	4.48E-02	0.123	2.28E-02	0.0974	4.49E-02	0.117
Total	**1.61E-01**	**0.0126**	**5.88E-02**	**0.162**	**3.40E-02**	**0.145**	**5.90E-02**	**0.153**
USE/APPLICATION								
Reflow application	1.49E+00	0.117	1.40E+00	3.84	1.09E+00	4.68	1.40E+00	3.65
Total	**1.49E+00**	**0.117**	**1.40E+00**	**3.84**	**1.09E+00**	**4.68**	**1.40E+00**	**3.65**
END-OF-LIFE								
Landfill	9.99E+02	78.3	1.05E+00	2.89	1.19E+00	5.08	1.60E+00	4.16
Incineration	2.59E+02	20.3	2.75E-01	0.757	3.10E-01	1.33	6.47E-01	1.68
Demanufacturing	1.46E-04	0.00001	1.27E-04	0.0003	1.49E-04	0.0006	1.27E-04	0.0003
Cu smelting	4.33E-02	0.0034	5.03E-02	0.138	N/A	N/A	1.21E-01	0.315
Unregulated	1.54E+01	1.20	1.50E+01	41.3	1.48E+01	63.3	2.27E+01	59.0
Total	**1.27E+03**	**99.9**	**1.64E+01**	**45.1**	**1.63E+01**	**69.7**	**2.51E+01**	**65.2**
GRAND TOTAL	**1.27E+03**	**100**	**3.64E+01**	**100**	**2.34E+01**	**100**	**3.85E+01**	**100**

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

Top Contributors to Aquatic Ecotoxicity Impacts (Paste Solder)

Table 3-99 presents the specific materials or flows contributing at least 1 percent of aquatic ecotoxicity impacts by solder. As expected from the results presented above, the SnPb impacts are dominated by the EOL stage. The aquatic ecotoxicity impacts are based on outputs to water. It is expected that the top contributors are lead emissions to water, mostly from landfilling, with a significant amount from incineration from leaching of incinerator ash disposed in landfills, and a smaller amount from unregulated recycling/disposal. Combined, lead emissions from these three processes constitute about 99.8 percent of the total life-cycle impacts. Lead emissions from landfilling alone are the largest contributor to SnPb impacts (78 percent). Further, lead emissions from landfilling are responsible for the fact that SnPb life-cycle impacts are far greater than those of the other alloys. This is partly a function of the higher leachability of lead, compared to the leachability of the other metals. For example, the fraction of lead in the SnPb alloy that was found to leach was approximately 0.19 (kg of Pb per kg of solder), compared to the fractions of 0.000019 and 0.000013 of silver and copper, respectively, in SAC (Chapter 2 and Appendix C).

Table 3-99. Top contributors to aquatic ecotoxicity impacts (paste solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	End-of-life	Solder landfilling (SnPb)	Lead emissions to water	78.3
	End-of-life	Solder incineration (SnPb)	Lead emissions to water	20.3
	End-of-life	Unregulated recycling and disposal (SnPb)	Lead emissions to water	1.20
SAC	Upstream	Silver production	Cadmium emissions to water	45.7
	End-of-life	Unregulated recycling and disposal (SAC)	Silver emissions to water	39.6
	Use/application	Electricity generation	Chlorine (dissolved) emissions to water	3.29
	End-of-life	Solder landfilling (SAC)	Silver emissions to water	2.42
	Upstream	Silver production	Lead emissions to water	2.13
	Upstream	Silver production	Zinc emissions to water	1.88
	End-of-life	Unregulated recycling and disposal (SAC)	Copper emissions to water	1.66
BSA	End-of-life	Unregulated recycling and disposal (BSA)	Silver emissions to water	63.3
	Upstream	Silver production	Cadmium emissions to water	21.2
	End-of-life	Solder landfilling (BSA)	Silver emissions to water	4.84
	Use/application	Electricity generation	Chlorine (dissolved) emissions to water	4.01
	End-of-life	Solder incineration (BSA)	Silver emissions to water	1.26
SABC	End-of-life	Unregulated recycling and disposal (SABC)	Silver emissions to water	32.8
	Upstream	Silver production	Cadmium emissions to water	27.8
	End-of-life	Unregulated recycling and disposal (SABC)	Copper emissions to water	26.2
	Use/application	Electricity generation	Chlorine (dissolved) emissions to water	3.13
	End-of-life	Solder landfilling (SACB)	Silver emissions to water	2.95
	Upstream	Silver production	Lead emissions to water	1.30
	End-of-life	Solder landfilling (SABC)	Copper emissions to water	1.21
	Upstream	Silver production	Zinc emissions to water	1.14
	End-of-life	Solder incineration (SABC)	Silver emissions to water	1.05

Another contributing factor leading to lead driving impacts, in addition to the leachability of lead, is that it has a relatively high aquatic toxicity measure (discussed below); however, lead does not have the highest relative aquatic toxicity compared to the other metals as it did for human health non-cancer toxicity.

Among the lead-free alloys, silver, cadmium, and copper emissions to water are the greatest contributors to aquatic ecotoxicity impacts. For SAC, cadmium emissions from silver production contribute 46 percent, and silver emissions from unregulated recycling and disposal contribute 40 percent. The remaining flows—chlorine emissions from reflow application, silver emissions from landfilling, lead and zinc emissions from silver production, and copper emissions from unregulated recycling and disposal—all contribute under 4 percent each to the total SAC ecotoxicity impacts.

For BSA, silver emissions from unregulated recycling and disposal contribute 63 percent, and cadmium emissions from silver production contribute nearly 20 percent to total aquatic ecotoxicity impacts. Silver emissions from landfilling, chlorine from electricity generation during reflow application, and silver emissions from incineration each contribute less than 5 percent.

The three top contributors to the SABC impacts are cadmium emissions from silver production (about 26 percent); and silver and copper emissions from unregulated recycling and disposal (27 percent each). The remaining top flows—chlorine from electricity generation for reflow application, silver and copper emissions from landfilling, lead and zinc emissions from silver production, and silver emissions from incineration—each contribute less than 4 percent to total impacts.

To help clarify the results, the aquatic ecotoxicity HVs for the top contributing flows are listed below in descending order of hazard (HVs for all materials classified as potentially toxic are presented in Appendix E):

- Cadmium: 28,500
- Silver: 10,050
- Copper: 2,732
- Lead: 976
- Zinc: 382
- Chlorine: 267

The HVs are relative values that rank the aquatic ecotoxicity potential of a chemical as compared to the average toxicity of many chemicals. The HVs are multiplied by the inventory output amounts for chemicals with potential aquatic ecotoxicity impacts to derive an impact score. Of the top contributors documented in Table 3-99, cadmium has the highest aquatic ecotoxicity HV, followed by silver. This helps explain why most impacts for the lead-free alternatives are driven by silver (from EOL processes) and cadmium (from silver production). For SnPb, on the other hand, the HV of lead is lower than cadmium and silver, however, the EOL output flows of silver and cadmium, both of which are a result of the presence of silver in the lead-free alloys, are not found in the SnPb inventory. Alternatively, the lead at EOL constitutes nearly all the impacts for SnPb, which are far greater than the total impacts for any of the other alloys.

3.2.13.3 Bar solder results

Total Aquatic Ecotoxicity Impacts by Life-Cycle Stage (Bar Solder)

Table 3-100 presents the bar solder results for aquatic ecotoxicity impacts by life-cycle stage, based on the impact assessment methodology presented above. The table lists the aquatic ecotoxicity impact scores per functional unit for the life-cycle stages of each bar solder alloy, as well as the percent contribution of each life-cycle stage to the total impacts. Figure 3-36 presents the results in a stacked bar chart.

Table 3-100. Aquatic ecotoxicity impacts by life-cycle stage (bar solder)

Life-cycle stage	SnPb		SAC		SnCu	
	Score*	%	Score*	%	Score*	%
Upstream	9.56E-02	0.0062	2.75E+01	13.9	7.03E-03	0.0808
Manufacturing	2.87E-01	0.0185	6.83E-02	0.0345	6.99E-02	0.804
Use/application	2.36E-01	0.0152	2.39E-01	0.120	2.39E-01	2.74
End-of-life	1.55E+03	99.96	1.70E+02	86.0	8.38E+00	96.4
Total	**1.55E+03**	**100**	**1.98E+02**	**100**	**8.70E+00**	**100**

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

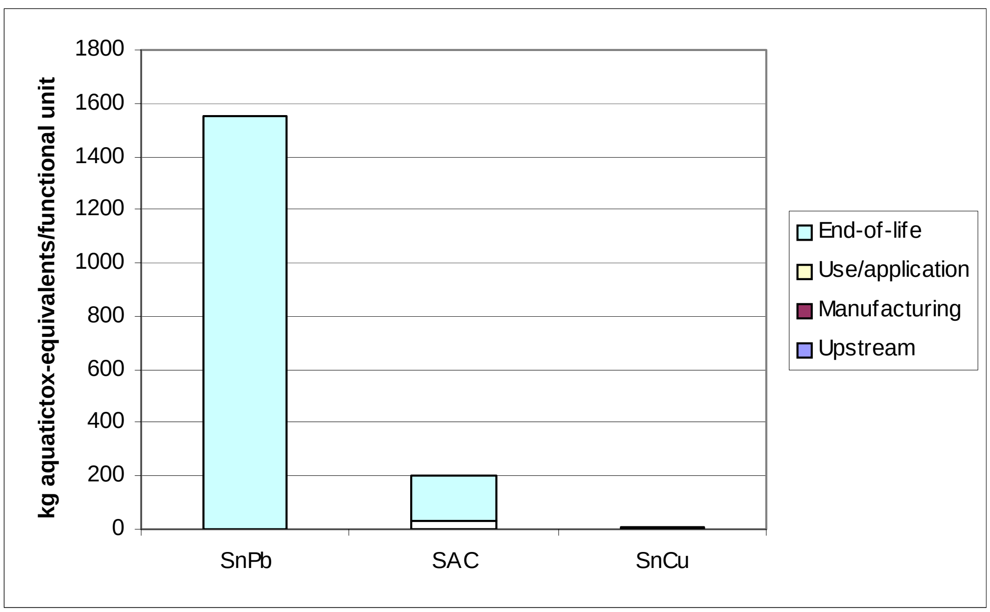

Figure 3-36. Bar Solder Total Life-Cycle Impacts: Aquatic Ecotoxicity

The total aquatic ecotoxicity impact score for SnPb (1,550 kg aquatictox-equivalents/functional unit) is far greater than the other bar solder alloys. SAC has the next greatest impact score (198 kg aquatictox-equivalents/functional unit), followed by SnCu with the lowest of 8.7 kg aquatictox-equivalents/functional unit.

The EOL stage accounts for nearly all of SnPb impacts, contributing 99.96 percent to the total aquatic ecotoxicity impact score. For the lead-free bar solder alternatives, the EOL stage is also the vast majority (96 and 86 percent), although the absolute scores are far lower than that of SnPb. For SAC, the upstream life-cycle stage contributes 14 percent to the total impacts.

The use/application stage is a small contributor to overall impacts for all three alloys, although it varies in terms of the percent contribution. Nonetheless, the aquatic ecotoxicity impact scores for all three alloys from this stage are all relatively small and close to one another in magnitude (0.236, 0.239, and 0.239 kg aquatictox-equivalents/functional unit for SnPb, SAC, and SnCu, respectively). Of note is that SnPb has a greater impact score for the use/application stage than the lead-free alloys, but the SnPb score only contributes 0.12 percent to SnPb total impacts. This is due to SnPb's high impact score at EOL. Impacts from the manufacturing stage are small, as are upstream impacts from SnPb and SnCu (all less than 0.3 kg aquatictox-equivalents/functional unit).

Aquatic Ecotoxicity Impacts by Process Group (Bar Solder)

Table 3-101 lists the aquatic ecotoxicity impacts of each of the process groups in the life-cycle of the bar solders. Within the EOL stage of the SnPb life-cycle, landfilling is the greatest contributor to total impacts (71 percent of total aquatic ecotoxicity impacts), followed by incineration (18 percent), and unregulated recycling/disposal (11 percent). Copper smelting and demanufacturing are small contributors to the total SnPb aquatic ecotoxicity impacts (0.0031 and 0.00001 percent, respectively).

When evaluating the lead-free alloys alone, unregulated recycling and disposal is the greatest process group contributor to EOL impacts, with scores of 169 and 7.89 kg aquatictox-equivalents/functional unit for SAC and SnCu, respectively (which contribute 85 and 91 percent of the total life-cycle impacts, respectively). The second greatest contributor to EOL impacts for the lead-free solders is landfilling (accounting for 0.6 or 4 percent of total impacts). For the lead-free alloys, unregulated recycling/disposal has far greater aquatic ecotoxicity impacts than landfilling, despite there being more electronics that are presumed to go to landfilling (72 percent) than unregulated disposal (4.5 percent). This is because only a small fraction of each metal in the lead-free bar alloys (between 0.000013 and 0.000027 for all metals) was found to leach during the project's leachability testing (Chapter 2 and Appendix C), but some 12.5 percent (i.e., a fraction of 0.125) of solder metals sent to unregulated recycling and disposal are assumed to be released directly to surface waters via surface water runoff from waste electronics burn piles.

Within the upstream life-cycle stage, silver production for SAC contributes nearly 14 percent while all the other metals production process groups are negligible contributors to the overall aquatic ecotoxicity impacts for all alloys. The use/application stage has only one process group contributing to that life-cycle stage: wave solder application. No further discussion on the breakdown of this life-cycle stage is warranted. Although the manufacturing life-cycle stage contributes a very small proportion to the overall impacts, Table 3-101 shows the contribution of the two process groups—solder manufacturing and post-industrial recycling—within the manufacturing stage. For all the alloys, post-industrial recycling has a greater aquatic ecotoxicity impact score than the solder manufacturing process group.

Table 3-101. Aquatic ecotoxicity impacts by life-cycle stage and process group (bar solder)

Life-cycle stage	**SnPb**		**SAC**		**SnCu**	
Process group	Score*	%	Score*	%	Score*	%
UPSTREAM						
Sn production	4.92E-04	0.00003	1.04E-03	0.0005	8.04E-04	0.0092
Pb production	9.51E-02	0.0061	N/A	N/A	N/A	N/A
Ag production	N/A	N/A	2.75E+01	13.9	N/A	N/A
Cu production	N/A	N/A	6.35E-03	0.0032	6.23E-03	0.0716
Total	**9.56E-02**	**0.0062**	**2.75E+01**	**13.9**	**7.03E-03**	**0.0808**
MANUFACTURING						
Solder manufacturing	3.57E-02	0.0023	4.12E-02	0.0208	2.37E-02	0.272
Post-industrial recycling	2.51E-01	0.0162	2.71E-02	0.0137	4.63E-02	0.532
Total	**2.87E-01**	**0.0185**	**6.83E-02**	**0.0345**	**6.99E-02**	**0.804**
USE/APPLICATION						
Solder application	2.36E-01	0.0152	2.39E-01	0.1204	2.39E-01	2.7426
Total	**2.36E-01**	**0.015**	**2.39E-01**	**0.1204**	**2.39E-01**	**2.74**
END-OF-LIFE						
Landfill	1.11E+03	71.4	1.18E+00	0.597	3.91E-01	4.49
Incineration	2.73E+02	17.5	2.93E-01	0.148	9.70E-02	1.12
Demanufacture	1.63E-04	0.00001	1.42E-04	0.0001	1.41E-04	0.0016
Cu smelting	4.81E-02	0.0031	1.57E-03	0.0008	1.52E-03	0.0175
Unregulated	1.71E+02	11.0	1.69E+02	85.2	7.89E+00	90.7
Total	**1.55E+03**	**99.96**	**1.70E+02**	**86.0**	**8.38E+00**	**96.4**
GRAND TOTAL	**1.55E+03**	**100**	**1.98E+02**	**100**	**8.70E+00**	**100**

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

Top Contributors to Aquatic Ecotoxicity Impacts (Bar Solder)

Table 3-102 presents the specific materials or flows contributing at least 1 percent of aquatic ecotoxicity impacts by solder. As expected from the results presented above, the SnPb impacts are dominated by the EOL stage. The aquatic ecotoxicity impacts are based on outputs to water. It is expected that the top contributors are lead emissions to water, mostly from landfilling, with a significant amount from incineration (from leaching of incinerator ash disposed in landfills), and a smaller amount from unregulated recycling/disposal. Lead emissions from landfilling alone are the largest contributor to SnPb impacts (71 percent), further, lead emissions from landfilling are responsible for the fact that SnPb life-cycle impacts are far greater than those of the other alloys. This is partly a function of the higher leachability of lead compared to the leachability of the other metals. For example, the fraction of lead in the SnPb alloy that was found to leach was approximately 0.19 (kg of Pb per kg of solder), compared to the fractions of 0.000019 (kg of Pb per kg of solder) and 0.000013 (kg of Pb per kg of solder) of silver and copper, respectively, in SAC (Chapter 2 and Appendix C).

Table 3-102. Top contributors to aquatic ecotoxicity impacts (bar solder)

Solder	Life-Cycle Stage	Process	Flow	% Contribution
SnPb	End-of-life	Solder landfilling (SnPb)	Lead to water	71.4
	End-of-life	Solder incineration (SnPb)	Lead to water	17.6
	End-of-life	Unregulated recycling and disposal (SnPb)	Lead to water	11.0
SAC	End-of-life	Unregulated recycling and disposal (SAC)	Silver to water	81.8
	Upstream	Silver production	Cadmium to water	12.5
	End-of-life	Unregulated recycling and disposal (SAC)	Copper to water	3.42
SnCu	End-of-life	Unregulated recycling and disposal (SnCu)	Copper to water	90.4
	End-of-life	Solder landfilling (SnCu)	Copper to water	4.49
	Use/application	Electricity generation	Chlorine (dissolved) to water	2.35
	End-of-life	Solder incineration (SnCu)	Copper to water	1.12

Another contributing factor leading to lead driving impacts, in addition to the leachability of lead, is that it has a relatively high aquatic toxicity measure (discussed below). Lead does not have the highest relative aquatic toxicity compared to the other metals as it did for human health non-cancer toxicity.

Among the lead-free bar alloys, silver, cadmium, copper, and chlorine emissions to water are top contributors to aquatic ecotoxicity impacts. For SAC, silver emissions from unregulated recycling and disposal contribute about 82 percent, cadmium emissions from silver production contribute about 13 percent, and copper emissions from unregulated recycling and disposal contribute 3 percent.

For SnCu, copper from unregulated recycling and disposal contributes the greatest at 90 percent. Copper emissions from landfilling and incineration, as well as chlorine from wave application, each contribute less than 5 percent to the total aquatic ecotoxicity impact scores.

As described earlier in Section 3.2.13.2, the aquatic ecotoxicity HVs for the top contributing flows for the bar solders are listed below in descending order of hazard (HVs for all materials classified as potentially toxic are presented in Appendix E):

- Cadmium: 28,500
- Silver: 10,050
- Copper: 2,732
- Lead: 976
- Chlorine: 267

To reiterate from previous sections, the HVs are relative values that rank the aquatic ecotoxicity potential of a chemical as compared to the average toxicity of many chemicals. The HVs are multiplied by the inventory output amounts for chemicals with potential aquatic ecotoxicity impacts to derive an impact score. Of the top contributors documented in Table 3-102, cadmium has the highest aquatic ecotoxicity HV, followed by silver, and then copper. This helps explain why most impacts for SAC are driven by silver from EOL processes, cadmium from silver production, and copper from EOL processes. For SnCu, copper emissions from EOL processes dominate impacts, and for SnPb, lead emissions dominate impacts. The large impact score for SnPb also is a function of the higher leachability of lead, as discussed above.

3.2.13.4 Limitations and uncertainties

The LCIA methodology for aquatic ecotoxicity impacts is subject to the same structural or modeling limitations and toxicity data limitations discussed previously for the occupational and public health impact categories. For a detailed discussion, refer to the *Limitations and Uncertainties* subsection of Section 3.2.11.4. One important distinction is that more toxicity data tend to be available for aquatic effects than for human carcinogenic effects, for example. Of the 178 chemicals classified as potentially toxic in this LFSP LCA, 53 had outputs to water that should be considered in the aquatic ecotoxicity impact category. Of these, 41 had aquatic ecotoxicity data suitable for inclusion in the LCIA

The LCI data limitations also are similar to those described in preceding sections. For SnPb, EOL processes dominate total impacts. As a result, the limitations and uncertainties for SnPb are most influenced by the EOL limitations and uncertainties. Most of the SnPb impacts are from outputs to water from landfilling or incineration processes as derived from leachability testing associated with this project (see Appendix C). As primary data collected for the purposes of the LFSP, the leachability data are considered to be of relatively low uncertainty; however, further information about their limitations and uncertainties was presented in Section 3.2.12.4 and is applicable here.

The lead-free alloy results for both paste and bar solders, on the other hand, are more influenced by limitations and uncertainties in the unregulated recycling/disposal inventory. (Emissions from landfilling also are among the top contributors to lead-free impacts in some cases and, thus, are subject to the limitations and uncertainties described for lead outputs from landfilling.) Unregulated recycling/disposal uncertainties are greater than those associated with landfill outputs due to the almost complete absence of analytical data on the partitioning of metals among environmental media for unregulated recycling and disposal processes. Data from EPA trials currently underway to assess metal emissions from open burning of electronics waste could be used later to reassess the assumptions used in this LCA for unregulated recycling and disposal processes.

For the other EOL processes, there also are uncertainties associated with the inventory quantities as they were based on assumptions about partitioning of the metals to various media, depending on the EOL process. For incineration, secondary literature was reviewed to make assumptions about metal releases and partitioning to various environmental media. This introduced slightly more uncertainty into the incineration outputs than is expected with the landfilling data. Uncertainties from copper smelting and unregulated recycling/disposal have less effect on the results as they both contribute small proportions to total impacts. Nonetheless, uncertainties associated with copper smelting arise from the inability of the researchers to obtain direct quantitative data from primary data sources, as was discussed previously.

In addition to metal output uncertainties from landfilling and incineration, there are EOL uncertainties related to the assumptions about EOL dispositions to each EOL process (e.g., 72 percent of solder goes directly to landfilling for SnPb, SAC, SABC, and SnCu). These are discussed in greater detail in Chapter 2, limitations and uncertainties in the EOL inventory).

In addition to the EOL stage, the aquatic ecotoxicity impact scores of the silver-bearing alloys are largely influenced by the upstream life-cycle stage. Upstream uncertainties have been discussed in previous sections and relate to the fact that the data are from secondary data sources. Silver production, which accounts for large amounts of the total aquatic ecotoxicity impacts for most of the lead-free solders, has associated uncertainties that are described in Section 3.2.1.4. As presented in that section, although the secondary silver data set from GaBi is considered "good," it is addressed with an alternate analyses in Section 3.3.

The use/application stage has a relatively small influence on the results. Nonetheless, the limitations and uncertainties related to electricity consumption and generation described previously apply here.

3.3 ALTERNATE ANALYSES

3.3.1 Reflow Application Energy Analysis

The energy requirements for the reflow application process are based on primary data collected from two facilities where test runs were conducted (described in Section 2.4). The two ovens in which these tests were performed represent different technologies resulting in a large range in energy consumption rates due to the difference in the efficiencies of the ovens. In the baseline analysis, an average energy consumption value from these two test runs was used in the determination of the life-cycle impacts reported earlier in Chapter 3. Table 3-103 shows the baseline energy consumption average and the low and high individual data points that were used to calculate the average. The low estimates are either 27 or 35 percent lower than the baseline and the high estimates are either 27 or 35 percent higher than the baseline.

Table 3-103. Energy estimates for the reflow application process

Alloy	Baseline energy*	Low energy*	Percent change from baseline	High energy*	Percent change from baseline
SnPb	115	73.9	-35	155	35
SAC	124	80.6	-35	168	35
BSA	82.4	60.1	-27	105	27
SABC	124	80.6	-35	168	35

* Units are in kWh/kg of solder applied to a printed wiring board. (*Note*: This unit is different from the impact results which are presented per unit *volume* of solder on a printed wiring board.)

For many of the impact categories evaluated, impacts from energy used in the use/application life-cycle stage constituted a majority of impacts. For paste solder, nearly all of the use/application energy consumption occurs during the reflow soldering process. Table 3-104 lists the impact categories, and the alloys within each category, for which a majority of the impacts resulted from the energy consumed during reflow. The only categories in which none of the alloys had a majority of their impacts from energy used during reflow application were occupational non-cancer, occupational cancer, public non-cancer, and aquatic ecotoxicity.

The analyses determine the sensitivity of the baseline impact results to the selection of a value for the energy used during reflow. To demonstrate the sensitivity, results of the baseline analysis were re-evaluated using the range of energy consumption values shown in Table 3-103 for the energy use impact category only. This category was selected as an example of the potential sensitivity because a large percentage (between about 81 and 92 percent) of the of the baseline impacts in this category for all four alloys resulted from the energy consumed during reflow.

Table 3-104. Impact categories and alloys with majority of impacts from energy used in reflow application of paste solders

Impact Category	Alloy(s)
Non-renewable resource use	SnPb, SAC, BSA, SABC
Renewable resource use	SnPb, SAC, BSA, SABC
Energy use	SnPb, SAC, BSA, SABC
Landfill space use	SnPb
Global warming	SnPb, SAC, BSA, SABC
Ozone depletion	SnPb, SAC, BSA, SABC
Photochemical smog	SnPb, BSA, SABC
Air acidification	SnPb, BSA, SABC
Air particulate matter	SnPb
Water eutrophication	SnPb, SAC, BSA, SABC
Water quality	SnPb, SAC, BSA, SABC
Public human health—cancer	SnPb, SAC, BSA, SABC

When the low and high energy data points are used to generate life-cycle impact results for each type of solder paste, the magnitude of the impact scores change; however, the relative comparison among alloys remains the same. As shown in Figure 3-37, for all three scenarios (low energy, baseline, and high energy), SAC has the highest impacts, followed by SABC, SnPb, and finally BSA.

When considering the contributions of individual life-cycle stages to the energy use impact category (Section 3.2.2), the portion of the total life-cycle energy use impacts attributable to the energy use during the use/application stage remain substantial, even when the low energy data are used. This is illustrated in Table 3-105, which shows the percent contribution of the use/application stage for the low energy, the baseline average, and the high energy data. The table shows that even using the low energy values (i.e., a 27 to 35 percent decrease in energy use in reflow application depending on the alloy), the energy impact results remain driven by the use/application stage (73 to 88 percent) compared to the baseline where 82 to 91 percent of impacts are from the use/application stage.

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

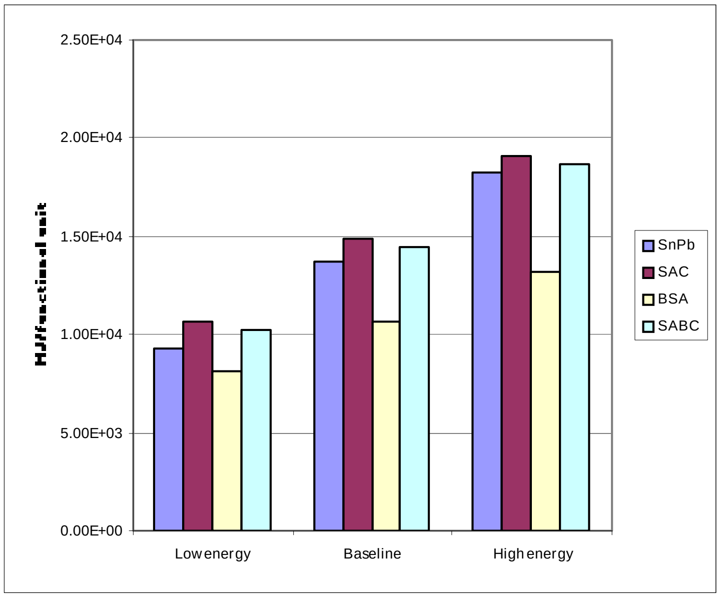

Figure 3-37. Sensitivity Analysis of Energy Consumption During Reflow Solder Application

Table 3-105. Use/application energy sensitivity analysis: percent contribution of use/application stage to energy impacts

Energy estimate	Percent Contribution			
	SnPb	**SAC**	**BSA**	**SABC**
Low energy	88.2	73.2	83.1	76.8
Baseline	91.2	78.9	85.8	82.0
High energy	94.0	85.1	89.5	87.4

3.3.2 Alternate Silver Inventory Analysis

Upstream silver production was the greatest contributing process group for many of the impact categories of the lead-free solder pastes in the baseline LCA. For SAC, six impact categories were dominated by the silver production process, including landfill space use, photochemical smog, air acidification, air particulates, public non-cancer, and aquatic ecotoxicity (presented in Table 3-120). For BSA, the landfill space use impact category had silver production as the top contributing process group; and for SABC, the landfill space use and the air particulate matter impact categories had silver production as the top contributing process group (see
Tables 3-121 and 3-122). As expected, SAC is more influenced by the silver production process group than the other alloys because of its greater silver content. In addition, the silver process contributed significantly to many other categories for each of the alloys, though it may not have been the dominant contributor.

Due to the large influence that silver production had on many of the impact categories, an alternate analysis to the baseline was performed by substituting an alternate silver data set (DEAM) for the GaBi silver mix data set used to calculate the baseline results. For a discussion of the GaBi data set and an explanation of why that data set was used for the baseline, please refer to Section 2.2. Tables 3-106 and 3-108 show the results of the alternate analyses for paste and bar solders respectively, as compared to the baseline. In the tables, bold entries indicate the highest impact score (i.e., the greatest environmental impacts) among the alloys within each impact category, while the shaded entries indicate the lowest impact score among alloys within each category.

The results of the alternate analysis are dramatic and can be readily observed in Table 3-123, which compares the baseline results for paste solders with those developed using the alternate DEAM silver data set. For the baseline analysis, SnPb had the highest impacts in six impact categories while SAC had the higher impacts in the remaining ten categories. Neither BSA nor SABC had impacts that were the highest impact score in any category; however, when results were generated using the DEAM data set, SnPb had the highest impacts in fourteen of the sixteen impact categories, with SAC (particulate matter) and BSA (NRR use) leading in one category each. In many cases, SAC was only slightly less than SnPb, and most likely within the error range of the data. Nonetheless, the analysis resulted in a noticeable change in relative results between SnPb and SAC. Likewise, SnPb had the lowest impact scores—indicating it was the best performer of the alloys evaluated—in five impact categories using the GaBi mixed silver data set, but did not register the lowest score in any impact category during the alternate analysis. BSA accounted for the lowest impact score in fifteen of the sixteen impact categories. These results indicate the high sensitivity of the overall life-cycle results for paste solders to the silver data set, and suggest that additional effort to further resolve the silver mining and extraction data would be well spent.

A comparison of the baseline and alternate analyses for bar solders is shown in Table 3-109. For the baseline analysis using the GaBi data set, SAC had highest life-cycle impacts in twelve impact categories while SnPb had highest impacts in the remaining four categories; however, results from the alternate analysis indicate that SAC had highest impacts in only seven impact categories and SnPb had highest impacts in nine impact categories. This is not as dramatic a change as was seen with the paste results; however, several impact-specific conclusions were altered. In addition, while SAC was not the lowest score for any impact categories in the baseline, it was the lowest in five impact categories in the alternate analysis. Again, this shows the importance of the silver inventory on results and the variability among different silver production data sets. The baseline is expected to be of good quality and is believed to be of greater quality than the DEAM data, but regardless of the relative quality of each data set, these results show the possible variability and sensitivity of the results to the silver inventory data.

Table 3-106. Alternative silver production analysis (paste solders)

Impact Category	Unit per functional unit*	Baseline				Alternate silver process			
		SnPb	**SAC**	**BSA**	**SABC**	**SnPb**	**SAC**	**BSA**	**SABC**
NRR use	kg	1.61E+03	**1.82E+03**	1.76E+03	1.72E+03	1.61E+03	1.52E+03	**1.67E+03**	1.53E+03
RR use	kg	**3.48E+04**	3.47E+04	2.64E+04	3.41E+04	**3.48E+04**	3.26E+04	2.58E+04	3.28E+04
Energy use	MJ	1.25E+04	**1.36E+04**	9.76E+03	1.31E+04	**1.25E+04**	1.24E+04	9.40E+03	1.24E+04
Landfill	m^3	2.75E-03	**1.62E-02**	6.57E-03	1.13E-02	**2.75E-03**	2.62E-03	2.53E-03	2.63E-03
Global warming	kg CO_2-Equiv.	8.17E+02	**8.73E+02**	6.31E+02	8.49E+02	**8.17E+02**	8.15E+02	6.14E+02	8.11E+02
Ozone depletion	kg CFC-11-equiv.	9.95E-05	**1.10E-04**	7.98E-05	1.04E-04	**9.95E-05**	9.35E-05	7.49E-05	9.39E-05
Photochemical smog	kg ethene-equiv.	3.13E-01	**6.18E-01**	3.61E-01	5.05E-01	**3.13E-01**	3.00E-01	2.66E-01	3.01E-01
Acidification	kg SO_2-equiv.	6.50E+00	**1.25E+01**	7.32E+00	1.03E+01	**6.50E+00**	6.30E+00	5.48E+00	6.30E+00
Particulate matter	kg	4.52E-01	**1.30E+00**	5.85E-01	1.01E+00	4.52E-01	**4.95E-01**	3.44E-01	4.88E-01
Eutrophication	kg phosphate-equiv.	**1.22E-01**	1.18E-01	9.06E-02	1.17E-01	**1.22E-01**	1.14E-01	8.95E-02	1.15E-01
Water quality	kg	1.79E-01	**2.26E-01**	1.64E-01	2.06E-01	**1.79E-01**	1.68E-01	1.47E-01	1.69E-01
Occupational non-cancer	kg noncancertox-equiv.	**5.60E+05**	8.12E+03	2.34E+03	5.25E+03	**5.60E+05**	1.02E+04	2.95E+03	6.57E+03
Occupational cancer	kg cancertox-equiv.	**7.74E+01**	7.41E+01	6.11E+01	7.58E+01	**7.74E+01**	7.30E+01	6.71E+01	7.30E+01
Public non-cancer	kg noncancertox-equiv.	**8.80E+04**	1.05E+04	5.01E+03	7.84E+03	**8.80E+04**	2.99E+03	2.76E+03	2.99E+03
Public cancer	kg cancertox-equiv.	6.96E+00	**7.05E+00**	5.15E+00	6.51E+00	**6.96E+00**	5.44E+00	4.67E+00	5.45E+00
Aquatic ecotoxicity	kg aquatictox-equiv.	**1.27E+03**	3.64E+01	2.34E+01	3.85E+01	**1.27E+03**	1.79E+01	1.79E+01	2.66E+01

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

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

Table 3-107. Comparison of baseline and alternate LCA analysis (paste solders)

Solder Alloy	Baseline High	Baseline Low	Alternate High	Alternate Low
SnPb	6	5	14	0
SAC	10	0	1	1
BSA	0	11	1	15
SABC	0	0	0	0

Table 3-108. Alternative silver production analysis (bar solders)

Impact Category	unit per functional unit*	Baseline			Alternate silver process		
		SnPb	SAC	SnCu	SnPb	SAC	SnCu
NRR use	kg	3.15E+02	**7.68E+02**	3.12E+02	3.15E+02	**3.29E+02**	3.12E+02
RR use	kg	6.03E+03	**8.76E+03**	5.83E+03	**6.03E+03**	5.75E+03	5.83E+03
Energy use	MJ	2.91E+03	**5.77E+03**	3.40E+03	2.91E+03	**4.04E+03**	3.32E+03
Landfill	m^3	1.34E-03	**2.14E-02**	1.33E-03	**1.34E-03**	1.31E-03	1.33E-03
Global warming	kg CO_2-Equiv.	1.87E+02	**3.57E+02**	2.16E+02	1.87E+02	**2.71E+02**	2.16E+02
Ozone depletion	kg CFC-11-equiv.	1.87E-05	**4.13E-05**	1.78E-05	**1.87E-05**	1.71E-05	1.78E-05
Photochemical smog	kg ethene-equiv.	6.98E-02	**5.51E-01**	7.06E-02	6.98E-02	**7.88E-02**	7.06E-02
Acidification	kg SO_2-equiv.	1.43E+00	**1.10E+01**	1.53E+00	1.43E+00	**1.81E+00**	1.53E+00
Particulate matter	kg	1.49E-01	**1.47E+00**	1.99E-01	1.49E-01	**2.78E-01**	1.99E-01
Eutrophication	kg phosphate-equiv.	2.14E-02	**2.57E-02**	2.06E-02	**2.14E-02**	2.02E-02	2.06E-02
Water quality	kg	3.98E-02	**1.20E-01**	3.64E-02	**3.98E-02**	3.37E-02	3.64E-02
Occ non-cancer	kg noncancertox-equiv.	**7.15E+05**	1.09E+04	6.53E+01	**7.15E+05**	1.39E+04	6.53E+01
Occ cancer	kg cancertox-equiv.	**5.94E+01**	5.75E+01	5.49E+01	**5.94E+01**	5.90E+01	5.49E+01
Public non-cancer	kg noncancertox-equiv.	**1.34E+05**	1.22E+04	7.33E+02	**1.34E+05**	1.01E+03	7.33E+02
Public cancer	kg cancertox-equiv.	6.87E+00	**1.24E+01**	9.96E+00	6.87E+00	**1.01E+02**	9.96E+00
Aquatic toxicity	kg aquatictox-equiv.	**1.55E+03**	1.98E+02	8.70E+00	**1.55E+03**	1.71E+02	8.70E+00

*The functional unit is 1,000 cc of solder applied to a printed wiring board.
Notes: Bold impact scores indicate the alloy with the highest score for an impact category.
Shaded impact scores indicate the alloy with the lowest score for an impact category.

Table 3-109. Comparison of baseline and alternate LCA analysis (bar solders)

Solder Alloy	Baseline High	Baseline Low	Alternate High	Alternate Low
SnPb	4	6	9	6
SAC	12	0	7	5
SnCu	0	10	0	5

3.3.3 Alternate Leachate Analysis

The leachability study conducted for this project was used to estimate the outputs of metals from landfilling PWB waste or residual metals in ash. Lead was found to leach to a much greater extent than the other metals in the solders being analyzed in this study. These leachability results contributed to the large public non-cancer and aquatic ecotoxicity impacts for the SnPb as compared to the other alloys for both the paste and the bar solder results (see Sections 3.2.12 and 3.2.13). Two major contributors to these high SnPb results were the high leachability of lead and the fact that the lead has a very high relative toxicity. The TCLP leachability study conducted to determine the landfilling outputs is based on standard EPA TCLP test protocol using acetic acid, a substance known to readily leach lead. It is unknown to what extent these test conditions represent actual landfill conditions, which can vary dramatically over the lifetime of a landfill. It should be noted that only two impact categories (public non-cancer and aquatic ecotoxicity) were largely influenced by the EOL landfilling process, with the SnPb alloy particularly affected in both cases. To determine the sensitivity of the results to the lead leachability data, this section presents the results of an alternate analysis using the detection limit of lead as a lower bound of possible lead leachability during the TCLP study.

For the alternate analysis, the measured fraction of lead detected in the leachate during leachability testing of 0.19 (the baseline analysis) was replaced with the fraction of 0.000021 based on the TCLP detection limit for lead (0.01 Pb). The life-cycle impacts for both the public non-cancer and the aquatic ecotoxicity categories were then recalculated.

Tables 3-110 and 3-111 present the paste and bar results, respectively, for both the baseline analysis and the alternate lead leachate analysis. As shown in the tables, even with the assumption that lead essentially does not leach (i.e., assuming the study detection limit for the leachability of lead), the SnPb alloy impacts scores are still at least 2.5 times higher than the score of the next closest alloy for public non-cancer impacts and a full order of magnitude higher for aquatic ecotoxicity; however, the relative differences between SnPb and the lead-free alloys are far less than in the baseline analysis.

Table 3-110. Alternative lead leachate analysis for selected impact categories in the paste solder results

Impact category	Unit per functional unit (b)	Baseline				Alternate lead leachate data			
		SnPb	SAC	BSA	SABC	SnPb	SAC	BSA	SABC
Public non-cancer	kg noncancertox-equiv.	**8.80E+04**	1.05E+04	5.01E+03	7.84E+03	**2.41E+04**	1.05e+04	5.01E+03	7.84E+03
Aquatic ecotoxicity	kg aquatictox-equiv.	**1.27E+03**	3.64E+01	2.34E+01	3.85E+01	**2.76E+02**	3.64E+01	2.34E+01	3.85E+01

(a) Impact categories selected are those that were highly impacted by the leachate data in the baseline analysis.
(b) The functional unit is 1,000 cc of solder on a printed wiring board.
Notes: Bold impact scores indicate the alloy with the highest score for an impact category.
Shaded impact scores indicate the alloy with the lowest score for an impact category.

Table 3-111. Alternative lead leachate analysis for selected impact categories in the bar solder results

Impact category	Unit per functional unit (b)	Baseline			Alternate lead leachate data		
		SnPb	**SAC**	**SnCu**	**SnPb**	**SAC**	**SnCu**
Public non-cancer	kg noncancertox-equiv.	**1.33E+05**	1.22E+04	7.26E+02	**6.23E+04**	1.22E+04	7.26E+02
Aquatic ecotoxicity	kg aquatictox-equiv.	**1.55E+03**	1.98E+02	8.70E+00	**4.44E+02**	1.98E+02	8.69E+00

(a) Impact categories selected are those that were highly impacted by the leachate data in the baseline analysis.
(b) The functional unit is 1,000 cc of solder on a printed wiring board.
Notes: Bold impact scores indicate the alloy with the highest score for an impact category.
Shaded impact scores indicate the alloy with the lowest score for an impact category.

These results are not completely unexpected given the high toxicity of lead compared to the other metals. This analysis suggests that any elevation of the leachability data for SnPb due to the aggressive nature of acetic acid towards the lead-based solder was unlikely to have changed the overall impacts for SnPb relative to the other solders. The SnPb alloy would still have the higher potential impacts for both public non-cancer and aquatic ecotoxicity than the other solder alloys, based primarily on its relative toxicity.

3.4 SUMMARY OF LIFE-CYCLE IMPACT ANALYSIS CHARACTERIZATION AND RESULTS

This section presents an overview of the characterization methods and the life-cycle impact results for the paste and bar solder alloys. Section 3.4.1 provides the equations for each impact category that are used to calculate impact scores. Section 3.4.2 describes the LCIA data sources and data quality. For both paste and bar solders, respectively, Sections 3.4.3 and 3.4.4 provide the total life-cycle impact category indicator scores for each alloy for each of the sixteen impact categories evaluated in this study.

The LFSP LCIA methodology does not perform the optional LCIA steps of normalization (calculating the magnitude of category indicator results relative to a reference value), grouping (scoring and possibly ranking of indicators across categories), or weighting (converting indicator results based on importance and possibly aggregating them across impact categories). Grouping and weighting, in particular, are subjective steps that depend on the values of different individuals, organizations, or societies performing the analysis. Since the LFSP involves a variety of stakeholders from different geographic regions and with different values, these more subjective steps were intentionally excluded from the LFSP LCIA methodology. Normalization also was intentionally not included as there are not universally accepted normalization reference values for all the impact categories included in this study. Furthermore, one of the primary purposes of this research is to identify the relative differences in the potential impacts among alloys, and normalization within impact categories would not affect the relative differences among alloys within the impact categories.

Section 3.4.5 summarizes the limitations and uncertainties associated with the LCIA methodology as well as the general limitations and uncertainties associated with the results.

3.4.1 Impact Score Equations

Table 3-112 summarizes the impact categories, associated impact score equations, and the input or output data required for calculating natural resource impacts. Each of these characterization equations are loading estimates. For a more detailed discussion of loading estimates, refer to Section 3.1.

Table 3-112. Summary of natural resources impact scoring

Impact category	Impact score approach	Data required from inventory (per functional unit)	
		Inputs	Outputs
Use of renewable resources	$IS_{RR} = Amt_{RR} \times (1 - RC)$	Material mass (kg) (e.g., water)	None
Use/depletion of non-renewable resources	$IS_{NRR} = Amt_{NRR} \times (1 - RC)$	Material mass (kg)	None
Energy use, general energy consumption	$IS_E = Amt_E$ or $(Amt_F \times H/D)$	Energy (MJ) (electricity, fuel)	None
Landfill space use	$IS_L = Amt_W / D$	None	Mass of waste (hazardous and solid waste combined) (kg) and density (e.g., volume, m^3)

Abbreviations: RC=recycled content; H=heat value of fuel *i*; D=density of fuel *i*.

The term abiotic ecosystem refers to the nonliving environment that supports living systems. Table 3-113 presents the impact categories, impact score equations, and inventory data requirements for abiotic environmental impacts to atmospheric resources.

Table 3-113. Summary of atmospheric resource impact scoring

Impact category	Impact score approach	Data required from inventory (per functional unit)	
		Inputs	Outputs
Global warming	$IS_{GW} = EF_{GWP} \times Amt_{GG}$	None	Amount of each greenhouse gas chemical released to air
Stratospheric ozone depletion	$IS_{OD} = EF_{ODP} \times Amt_{ODC}$	None	Amount of each ozone depleting chemical released to air
Photochemical smog	$IS_{POCP} = EF_{POCP} \times Amt_{POC}$	None	Amount of each smog-creating chemical released to air
Acidification	$IS_{AP} = EF_{AP} \times Amt_{AC}$	None	Amount of each acidification chemical released to air
Air quality (particulate matter)	$IS_{PM} = Amt_{PM}$	None	Amount of particulates: PM_{10} or TSP released to air [a]

[a] Assumes PM_{10} and TSP are equal; however, using TSP will overestimate PM_{10}.

Table 3-114 presents the impact categories, impact score equations, and required inventory data for abiotic environmental impacts to water resources.

Table 3-114. Summary of water resource impact scoring

Impact category	Impact score approach	Data required from inventory (per functional unit)	
		Inputs	Outputs
Water eutrophication	$IS_{EUTR} = EF_{EP} \times Amt_{EC}$	None	Amount of each eutrophication chemical released to water
Water quality (BOD and TSS)	$IS_{WQ} = Amt_{BOD} + Amt_{BOD}$	None	Amount of BOD and suspended solids (TSS) in each wastewater stream released to surface water
Water quality (TSS)	$IS_{TSS} = Amt_{TSS}$	None	Amount of suspended solids (TSS) in each wastewater stream released to surface water

Table 3-115 summarizes the human health and ecotoxicity impact scoring approaches. The impact categories, impact score equations, the type of inventory data, and the chemical properties required to calculate impact scores are presented. The human health effects and ecotoxicity impact scores are based on the scoring of inherent properties approach to characterization. For a more detailed discussion of characterization methods, refer to Section 3.1.

Table 3-115. Summary of human health and ecotoxicity impact scoring

Impact category	Impact score equations	Data required from inventory (per functional unit)		Chemical properties data required
		Inputs	Outputs	
Chronic human health effects—occupational, cancer	$IS_{CHO-CA} = HV_{CA} \times Amt_{TCinput}$	Mass of each primary and ancillary toxic chemical	None	WOE or SF
Chronic human health effects—occupational, noncancer	$IS_{CHO-NC} = HV_{NC} \times Amt_{TCinput}$	Mass of each primary and ancillary toxic chemical	None	Mammal NOAEL or LOAEL
Chronic human health effects—public, cancer	$IS_{CHP-CA} = HV_{CA} \times Amt_{TCoutput}$	None	Mass of each toxic chemical released to air and surface water	WOE or SF
Chronic human health effects—public, noncancer	$IS_{CHP-NC} = HV_{NC} \times Amt_{TCoutput}$	None	Mass of each toxic chemical released to air and surface water	Mammal NOAEL or LOAEL
Aquatic ecotoxicity	$IS_{AQ} = (HV_{FA} + HV_{FC}) \times Amt_{TCoutput,water}$	None	Mass of each toxic chemical released to surface water	Fish LC_{50} and/or fish NOEL

Individual impact scores are calculated for inventory items for a certain impact category and can be aggregated by inventory item (e.g., a certain chemical), process, life-cycle stage, or entire product profile. For example, global warming impacts can be calculated for one inventory item (e.g., CO_2 releases), for one process that could include contributions from several inventory items (e.g., electricity generation), for a life-cycle stage that may consist of several process steps (e.g., product manufacturing), or for an entire profile (e.g., a functional unit of a solder).

3.4.2 LCIA Data Sources and Data Quality

Data that are used to calculate impacts come from: (1) equivalency factors or other parameters used to identify hazard values; and (2) LCI items. Equivalency factors and data used to develop hazard values presented in this methodology include GWP, ODP, POCP, AP, EP, WOE, SF, mammalian LOAEL/NOAEL, fish LC_{50}, and fish NOEL. Published lists of the chemical-specific parameter values exist for GWP, ODP, POCP, AP, and EP (see Appendix D). The other parameters may exist for a large number of chemicals, and several data sources must be searched to identify the appropriate parameter values. Priority is given to peer-reviewed databases (e.g., Health Effects Assessment Summary Tables [HEAST], Integrated Risk Information System [IRIS], Hazardous Substances Data Bank [HSDB]), next other databases (e.g., Registry of Toxic Effects of Chemical Substances [RTECS]), then other studies or literature, and finally estimation methods (e.g., structure-activity relationships [SARs] or quantitative structure-activity relationships [QSARs]). The specific toxicity data that are used in the LFSP are presented in Appendix E.

The sources of each parameter presented in this report and the basis for their values are presented in Table 3-116. Data quality is affected by the data source itself, the type of data source (e.g., primary versus secondary data), the currency of the data, and the accuracy and precision of the data. The sources and quality of the LCI data used to calculate impact scores were discussed in Chapter 2. Data sources and data quality for each impact category are discussed further in Section 3.2, LCIA Results.

Table 3-116. Data sources for equivalency factors and hazard values

Parameter	Basis of parameter values	Source
Global warming potential	Atmospheric lifetimes and radiative forcing compared to CO_2	IPCC, 2001
Ozone depletion potential	The change in the ozone column in the equilibrium state of a substance compared to CFC-11	UNEP, 2003; WMO 1999
Photochemical oxidant creation potential	Simulated trajectories of ozone production with and without VOCs present compared to ethene	Heijungs *et al.*, 1992; EI, 1999
Acidification potential	Number of hydrogen ions that can theoretically be formed per mass unit of the pollutant being released compared to SO_2	Heijungs *et al.*, 1992; Hauschild and Wenzel, 1997
Nutrient enrichment/eutrophication potential	Ratio of N to P in the average composition of algae ($C_{106}H_{263}O_{110}N_{16}P$) compared to phosphate (PO_4^{3-})	Heijungs *et al.*, 1992; Lindfors *et al.*, 1995

Table 3-116. Data sources for equivalency factors and hazard values

Parameter	Basis of parameter values	Source
Weight-of-evidence	Classification of carcinogenicity by EPA or IARC based on human and/or animal toxicity data	EPA, 1999; IARC, 1998
Slope factor	Measure of an individual's excess risk or increased likelihood of developing cancer if exposed to a chemical, based on dose-response data	IRIS and HEAST as cited in RAIS online database
Mammalian: LOAEL/NOAEL	Mammalian (primarily rodent) toxicity studies	IRIS, HEAST and various literature sources provided by EPA and/or UT contractor
Fish lethal concentration to 50 percent of the exposed population (LC_{50})	Fish (primarily fathead minnow) toxicity studies	Various literature sources and Ecotox database
Fish NOEL	Fish (primarily fathead minnow) toxicity studies	Literature sources and Ecotox database

3.4.3 Paste Solder Results Summary

The indicator results presented throughout the remainder of this section are the result of the characterization step of the LCIA methodology where LCI results are converted to common units and aggregated within an impact category. Results are expressed in units specific to an individual impact category and, therefore, cannot be summed or compared across impact categories.

Table 3-117 presents a summary of the paste solder results for each impact category calculated using the impact assessment methodology presented in previous subsections of Section 3.2. Impact scores shown in bold indicate the alloy with the highest impact score in an impact category, while shaded scores indicate the alloy with the lowest impact score. SnPb has the greatest impact category indicator in six impact categories, including eutrophication, RR use, and four toxicity-related categories—public non-cancer, occupational non-cancer, occupational cancer, and aquatic ecotoxicity. SAC has the highest impact category indicator in the remaining ten impact categories: NRR use, energy use, landfill space use, global warming, ozone depletion, photochemical smog, acidification, particulate matter, water quality, and public cancer. SnPb has the lowest impact category indicator among the alloys in five impact categories: NRR use, landfill space use, photochemical smog, acidification, and particulate matter. BSA has the lowest indicators in the remaining eleven categories.

When evaluating the lead-free alternatives alone, without considering SnPb, BSA has the lowest life-cycle impact score in all categories and SAC has the highest in all categories, except aquatic ecotoxicity and occupational cancer, for which SABC has the highest impact scores. Both impacts scores, however, are not much greater than those for SAC, and all the lead-free alloys have substantially lower aquatic ecotoxicity impacts than SnPb. These scores only indicate the relative or incremental differences among the alloys and do not necessarily indicate any level of concern. The LCIA is not intended to quantify the significance of any particular impact score, but instead it shows the relative difference among the alloys within a particular impact category; however, for some impact categories, especially the toxicity categories, results are not necessarily linear. In other words, a score of ten does not mean potential impacts are ten times worse than a score of one. Detailed discussions of the results of each impact category, along with the associated uncertainties, are presented in Section 3.2.2.

Table 3-117. Paste solder LCIA results

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

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

Table 3-118 summarizes the top contributing life-cycle stages for each alloy by impact category. The life-cycle stage or stages that contribute fifty percent or more to impacts in each impact category are listed in the table. In cases where an individual life-cycle stage did not constitute a majority, the top stages that together exceed fifty percent are listed. In these cases, the life-cycle stage listed first represents the one with a greater percentage of impacts attributable to that impact category.

As shown in the table, the use/application life-cycle stage dominates much of the impacts. For SnPb, thirteen out of sixteen impact categories have the majority of their impacts from the use/application stage. The manufacturing stage dominates in one category: occupational non-cancer, although it is not a majority by itself. The EOL stage is a top contributor to occupational non-cancer and a majority for two other toxicity-related impact categories, public non-cancer and aquatic ecotoxicity. The EOL impacts affected by outputs are based on the metal constituents of the solders and not other materials in a PWB or the product which houses the PWB; that is, outputs from incineration include only the solder metals and not combustion products of the PWB itself. An analysis of an entire PWB assembly would likely result in differing impacts than shown in this analysis.

Table 3-118. Solder paste life-cycle stages contributing a majority of impacts

Impact category	SnPb	SAC	BSA	SABC
Non-renewable resource use	Use/application	Use/application	Use/application	Use/application
Renewable resource use	Use/application	Use/application	Use/application	Use/application
Energy use	Use/application	Use/application	Use/application	Use/application
Landfill space use	Use/application	Upstream	Upstream	Upstream
Global warming	Use/application	Use/application	Use/application	Use/application
Ozone depletion	Use/application	Use/application	Use/application	Use/application
Photochemical smog	Use/application	Upstream	Use/application	Use/application
Air acidification	Use/application	Upstream	Use/application	Use/application
Air particulates	Use/application	Upstream	Upstream	Upstream
Water eutrophication	Use/application	Use/application	Use/application	Use/application
Water quality	Use/application	Use/application	Use/application	Use/application
Occupational health—non-cancer	Manufacturing, End-of-life	Manufacturing, End-of-life	End-of-life, Use/application	Manufacturing, End-of-life
Occupational health—cancer	Use/application	Use/application	Use/application	Use/application
Public human health—non-cancer	End-of-life	Upstream	Upstream	Upstream
Public human health—cancer	Use/application	Use/application	Use/application	Use/application
Aquatic ecotoxicity	End-of-life	Upstream	End-of-life	End-of-life

For the lead-free alternatives, the upstream life-cycle stage plays a more important role than it does for SnPb. SAC has nine impact categories where the use/application stage is the majority contributor and six categories in which the upstream stage provides the majority of impacts. Manufacturing and EOL are top contributors to only one impact category: occupational non-cancer. The BSA impacts are driven by the use/application stage in eleven categories, the upstream stage in three categories, and the EOL in two categories. Manufacturing, along with EOL, contributes to the majority of impacts in the occupational non-cancer impact category. The impact categories for SABC are driven by the same stages as BSA, with the exception of the occupational non-cancer impact category. SABC occupational non-cancer impacts are driven by the manufacturing and EOL stages, as is the case for SnPb and SAC.

For all categories that are dominated by the use/application stage, except occupational non-cancer, impacts are from the electricity generation for the reflow application process. For occupational non-cancer, the use/application stage dominates from the actual reflow application process. In most cases where the upstream stage dominates impacts in a category, it is silver production that is responsible for the high impacts, as is illustrated in the tables that follow. In the manufacturing stage, which contributes significantly to occupational non-cancer for SnPb, SAC, and SABC, it is the solder manufacturing process that is the source.

As stated in the previous sections, because the use/application stage is so dominant, a sensitivity analysis of the use/application energy is provided in Section 3.3. Additionally, alternative analyses are conducted with (1) alternative silver production process data, and (2) the results of the less aggressive leachability study for EOL processes. These are also presented in Section 3.3.

Table 3-119 through 3-122 list the top contributing flows and their associated processes and life-cycle stages for each impact category for each of the solders. The tables show that for each alloy nearly all impact categories are driven by a different flow. For example, in the SnPb life-cycle, hard coal is the top contributor to energy impacts, sulphur dioxide is the top contributor to photochemical smog, and COD is the top contributor to water eutrophication (e.g., nutrient enrichment).

There are some flows that are top contributors to more than one impact category. For example, sulphur dioxide that drives photochemical smog and air acidification in the SnPb life-cycle is from electricity generation associated with reflow application. In the lead-free solder life-cycles, sulphur dioxide is the top contributor to three categories: photochemical smog, air acidification, and public human health (non-cancer); however, in these cases, the sulphur dioxide is from silver production in the upstream life-cycle stage, as opposed to electricity generation for reflow application in the case of SnPb.

Another top flow in the SnPb life-cycle that contributes to more than one category is lead emissions to water from landfilling. This is essentially the leachate from landfilling the SnPb alloy. Lead emissions to water contribute 72.6 percent to the public health (non-cancer) impact category and 78.3 percent to the aquatic ecotoxicity impact category.

In several instances, the top contributing individual flows comprise a large majority of the total contribution to the alloy’s life-cycle impacts within a category. For example, COD constitutes 97.1 percent of the total water eutrophication impacts. As there are not a large amount of chemicals for which there are eutrophication potentials, and the inventory in this project only has a few water eutrophying chemicals, it is understandable that one material might greatly dominate impacts. This is true for COD, despite its relatively low eutrophication potential (see Appendix D).

Many top contributors constitute a majority of the total impacts within a category. In the SnPb results, eleven of the sixteen impact categories had top flows representing a majority of total impacts.

By contrast, for lead-free solders, only seven of the sixteen categories had flows contributing fifty percent or more. For each alloy, however, they were not always the same impact categories that contribute greater than fifty percent. For example, with aquatic ecotoxicity, silver emissions to water from unregulated recycling/disposal of BSA (Table 3-121) contribute sixty-three percent, while cadmium emissions to water from silver production for SAC (Table 3-120) are only forty-six percent of total aquatic ecotoxicity impacts.

Table 3-119. Top contributing flows to SnPb solder paste impacts

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

Table 3-120. Top contributing flows to SAC solder paste impacts

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

Table 3-121. Top contributing flows to BSA solder paste impacts

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

Table 3-122. Top contributing flows to SABC solder paste impacts

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

3.4.4 Bar Solder Results Summary

Table 3-123 presents a summary of the bar solder results for each impact category calculated using the impact assessment methodology presented in previous subsections of Section 3.2. Impact scores shown in bold indicate the alloy with the highest impact score in an impact category, while shaded scores indicate the alloy with the lowest impact score. SnPb has the greatest impact category indicator in four impact categories, all of which are toxicity-related categories—public non-cancer, occupational non-cancer, occupational cancer, and aquatic ecotoxicity. SAC has the highest impact category indicator in the remaining twelve impact categories. SnPb has the lowest impact category indicator among the alloys in five impact categories: energy use, global warming, photochemical smog, acidification, and particulate matter. BSA has the lowest indicators in the remaining eleven categories.

When evaluating the lead-free alternatives alone, without considering SnPb, SAC has the highest impact score in all sixteen of the categories evaluated. Conversely, SnCu had the lowest indicator scores. These scores only indicate the relative or incremental differences among the alloys and do not necessarily indicate any level of concern. The LCIA is not intended to quantify the significance of any particular impact score, but instead it shows the relative difference among the alloys within a particular impact category. Detailed discussions of the results of each impact category, along with the associated uncertainties, are presented in Section 3.2.2.

Table 3-123. Bar solder LCIA results

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

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

Table 3-124 summarizes the top contributing life-cycle stages for each alloy by impact category. The life-cycle stage or stages that contribute fifty percent or more to impacts in each impact category are listed in the table. In cases where an individual life-cycle stage did not constitute a majority, the top stages that together exceed fifty percent are listed. In these cases, the life-cycle stage listed first represents the one with a greater percentage of impacts attributable to that impact category.

Table 3-124. Bar solder life-cycle stages contributing a majority of impacts

Impact category	SnPb	SAC	SnCu
Non-renewable resource use	Use/application	Upstream	Use/application
Renewable resource use	Use/application	Use/application	Use/application
Energy use	Use/application	Upstream	Use/application
Landfill space use	End-of-life	Upstream	End-of-life
Global warming	Use/application	Upstream	Use/application
Ozone depletion	Use/application	Upstream	Use/application
Photochemical smog	Use/application	Upstream	Use/application
Air acidification	Use/application	Upstream	Use/application
Air particulates	Upstream	Upstream	Upstream
Water eutrophication	Use/application	Use/application	Use/application
Water quality	Use/application	Upstream	Use/application
Occupational health—non-cancer	End-of-life, Manufacturing	End-of-life, Manufacturing	Use/application, Manufacturing
Occupational health—cancer	Use/application, Manufacturing	Use/applications, Upstream	Use/application, Manufacturing
Public human health—non-cancer	End-of-life	Upstream	Use/application
Public human health—cancer	Use/application	Use/application	Use/application
Aquatic ecotoxicity	End-of-life	End-of-life	End-of-life

As shown in the table, the use/application life-cycle stage dominates the impacts. For SnPb, eleven of the sixteen impact categories are driven by contributions from the use/application stage, with end-of-life processes dominating four other impact categories. Similarly, the use/application stage is the major contributor to thirteen of the impact categories for the SnCu alloy. Upstream and end-of-life processes contribute the majority of the impacts in the remaining SnCu impact categories. The manufacturing stage dominates in one category: occupational non-cancer, although it is not a majority by itself. The EOL impacts affected by outputs are based on the metal constituents of the solders and not other materials in a PWB or the product which houses the PWB; that is, outputs from incineration include only the solder metals and not combustion products of the PWB itself. An analysis of an entire PWB assembly would likely result in differing impacts than shown in this analysis.

For the lead-free solder alternative, SAC, the upstream life-cycle stage plays a more important role than it does for SnPb. SAC has ten impact categories where the upstream stage is the majority contributor, while the use/applications stage dominates another four categories. Like the other two solders, the end-of-life stage drives the aquatic ecotoxicity impact category.

Table 3-125 through 3-127 list the top contributing flows and their associated processes and life-cycle stages for each impact category for each of the solders. For all categories that are dominated by the use/application stage, except for occupational and public health categories, impacts result from the electricity generation for the wave application process. For the public and occupational health categories, the use/application stage dominates from the actual wave application process. As stated in the previous sections, because the use/application stage is so dominant, a sensitivity analysis of the use/application energy is provided in Section 3.3. Additionally, alternative analyses are conducted with (1) alternative silver production process data, and (2) the results of the less aggressive leachability study for EOL processes. These are also presented in Section 3.3.

The tables show that for each alloy nearly all impact categories are driven by a different flow. Silver production is the primary process driving many of the upstream impacts for SAC, yet as many as six different material flows resulting from silver production are responsible for being the major contributor in any one impact category. For example, suspended solids from silver production drive the water quality impacts, while halon (1301) is the largest contributor to ozone depletion. Only the release of sulfur dioxide to air during extraction and processing of silver is the major contributor in more than one impact category driven by silver production. For SnCu and SnPb bar solders, natural gas and dust releases to air from tin production are the only releases from upstream processes that make up a majority contribution to the impact categories.

There are some flows that are top contributors to more than one impact category, though they may originate from separate processes. For example, sulphur dioxide that drives photochemical smog and air acidification in the SnPb life-cycle is from electricity generation associated with reflow application. In the SAC solder life-cycle, sulphur dioxide is the top contributor to three categories: photochemical smog, air acidification, and public human health (non-cancer). In these cases, however, the sulphur dioxide is from silver production in the upstream life-cycle stage, as opposed to electricity generation for the wave application in the case of SnPb.

Another top flow in the SnPb life-cycle that contributes to more than one category is lead emissions to water from landfilling. This is essentially the leachate from landfilling the SnPb alloy. Lead emissions to water contribute 53.3 percent to the public health (non-cancer) impact category and 71.4 percent to the aquatic ecotoxicity impact category. As mentioned above, refer to Section 3.3 for an alternate analysis of these impacts using a less aggressive leachability test method.

In several instances, the top contributing individual flows comprise a large majority of the total contribution to the alloy's life-cycle impacts within a category. For example, COD constitutes 87.4 percent of the total water eutrophication impacts from SnPb bar solder. As there is not a large amount of chemicals for which there are eutrophication potentials and the inventory in this project only has a few water eutrophying chemicals, it is understandable that one material might greatly dominate impacts. This is true for COD, despite its relatively low eutrophication potential (see Appendix D).

Many top contributors constitute a majority of the total impacts within a category, though the bar solder results are dominated by one flow less than the paste solders. For SnPb solder paste, eleven of the sixteen impact categories had top flows representing a majority of total impacts, while only eight of the sixteen categories for bar solder had a leading contributor of more than fifty percent. SAC and SnCu solders had contributions greater than fifty percent in eight and nine categories respectively.

Table 3-125. Top contributing flows to SnPb bar solder impacts

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

Table 3-126. Top contributing flows to SAC bar solder impacts

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

Table 3-127. Top contributing flows to SnCu bar solder impacts

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

3.4.5 Limitations and Uncertainties

3.4.5.1 General LCIA methodology limitations and uncertainties

This section summarizes some of the limitations and uncertainties in the LCIA methodology in general. Specific limitations and uncertainties in each impact category are discussed in Sections 3.2.2 through 3.2.13 with the LCIA results for the LFSP.

The purpose of an LCIA is to evaluate the *relative potential* impacts of a product system for various impact categories. There is no intent to measure the *actual* impacts or to provide spatial or temporal relationships linking the inventory to specific impacts. The LCIA is intended to provide a screening-level evaluation of impacts.

In addition to lacking temporal or spatial relationships and providing only relative impacts, LCA also is limited by the availability and quality of the inventory data. Data collection can be time-consuming and expensive, and confidentiality issues may inhibit the availability of primary data.

Uncertainties are inherent in each parameter described in Table 3-112 through 3-115. For example, toxicity data require extrapolations from animals to humans and from high to low doses (for chronic effects), resulting in a high degree of uncertainty. Sources for each type of data should be consulted for more information on uncertainties specific to each parameter.

Uncertainties exist in chemical ranking and scoring systems, such as the scoring of inherent properties approach used for human health and ecotoxicity effects. In particular, systems that do not consider the fate and transport of chemicals in the environment can contribute to misclassifications of chemicals with respect to risk. Uncertainty is introduced where it was assumed that all chronic endpoints are equivalent, which is likely not the case. In addition, when LOAELs were not available but NOAELs were, a factor of ten was applied to the NOAEL to estimate the LOAEL, thus introducing uncertainty. The human health and ecotoxicity impact characterization methods presented in the LFSP LCIA are screening tools that cannot substitute for more detailed risk characterization methods; however, the methodology is an attempt to consider chemical toxicity at a screening level for potentially toxic materials in the inventory.

Uncertainty in the inventory data depends on the responses to the data collection questionnaires and other limitations identified during inventory data collection. These uncertainties are carried into the impact assessment. Uncertainties in the inventory data include, but are not limited to, the following:

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

The goal definition and scoping process helped reduce the uncertainty from missing data, although it is assured that some missing data still exist. The remaining uncertainties were reduced primarily through quality assurance/quality control measures (e.g., performing systematic double-checks of all calculations on manipulated data). The limitations and uncertainties in the inventory data were discussed further in Chapter 2.

3.4.5.2 General limitations and uncertainties of results

Limitations and uncertainties in LFSP LCIA results are due to limitations and uncertainties inherent in LCIA methodology itself, as well as limitations and uncertainties in the project LCI data. General limitations and uncertainties in the LCIA methodology were discussed above, and limitations and uncertainties in the project inventory were discussed in Chapter 2. In addition, particular limitations and uncertainties as they pertain to individual impact category results are presented in Sections 3.2.2 through 3.2.13.

The overall limitations and uncertainties associated with the results of each impact category are summarized in Tables 3-117 and 3-123 as relative DQIs. The DQI are qualitative indicators representing a high (H), medium (M), or low (L) level of overall quality, or some combination thereof.

For example, most categories in the paste solder results presented in Table 3-117 are given a medium-to-high relative DQI. Those with lower DQIs include ozone depletion, occupational cancer, and public cancer. Listed below by impact category are the relative DQI measures (in parentheses) and the major sources of uncertainty for those categories:

- Non-renewable and renewable resource use (M-H)—reflow application energy variability and the use of secondary electricity generation data;
- Energy use (H)—reflow application energy variability;
- Landfill space use (M-H)—the use of secondary upstream data;
- Global warming (H)—reflow application energy variability;
- Ozone depletion (L-M)—several ozone depleting chemicals in the inventories (from secondary data sources) are scheduled to have been phased out;
- Photochemical smog, acidification, and air particulates (M-H)—depends somewhat on secondary upstream data;
- Eutrophication and water quality (H)—the use of secondary electricity generation data;
- Occupational and public non-cancer and aquatic ecotoxicity (M-H)—uncertainty in the EOL leachate study; and
- Occupational and public cancer (L-M)—lack of carcinogenicity data for most chemicals.

Details of the uncertainties that contribute to the overall data quality for each impact category are presented in Sections 3.2.2 through 3.2.13.

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