APPENDIX A:
LCI DATA COLLECTION FORMS

DESIGN FOR THE ENVIRONMENT
LEAD-FREE SOLDER PROJECT

Life-Cycle Inventory (LCI) Data Collection Form

For Solder Manufacturers

Introduction

The Design for the Environment (DfE) Program in the U.S. Environmental Protection Agency's (EPA) Office of Pollution Prevention and Toxics has begun a voluntary, cooperative project with the electronics industry to assess the life-cycle environmental impacts of solder alternatives. The DfE Program conducts comparative analyses of alternative products or processes to provide businesses with data to make environmentally informed choices about product or process improvements. The DfE Program has no regulatory or enforcement agenda and was established to act as a partner with industry to promote pollution prevention. This environmental life-cycle assessment will address human and environmental impacts (e.g., energy, natural resource use, global warming, chronic toxicity) of various solders. The University of Tennessee (UT) Center for Clean Products and Clean Technologies is conducting the life-cycle inventory (LCI), which is the data collection phase of a life-cycle assessment, with technical assistance from the Electronic Industries Alliance (EIA), IPC -- Association Connecting Electronics Industries, and other partners.

Boundaries

A life-cycle assessment considers impacts from materials acquisition, material manufacturing, product manufacturing, use, and final disposition of a product. The LCI data are intended to be used to evaluate relative environmental impacts over the entire life-cycle of a product. In this project, the product is a type of solder. Therefore, data associated with the materials and processes used directly in the manufacturing, use, and disposition of the product are relevant to the LCI and requested in this form. You will not need to include materials or energy not directly used in the production of the solder (e.g., general building heating and air conditioning).

Product focus

This project will evaluate tin-lead solder (for wave and reflow operations)
and consider the following lead-free alternatives:

- -- Sn/Cu (wave)
- -- Sn/Ag/Cu (wave and reflow)
- -- Sn/Ag/Bi or Sn/Ag/Cu/Bi (reflow)

Most recent (or projected) production data are desired.

Inventory data

We are asking for data on one or multiple "product(s) of interest" that you manufacture, which may be one as defined above under Product Focus. The inputs and outputs data (Fig. 1) that you provide will be aggregated in the LCI to quantify the overall inputs and outputs of a solder alternative over its life-cycle. A separate form should be completed for each solder of interest.

Data sources

Much of the requested information can be drawn from existing sources, including, but not limited to the following:

1. Purchase and production records
2. Bills and invoices
3. Material Safety Data Sheets (MSDS)
4. Toxic Release Inventory (TRI) forms
5. Audit and analysis results (e.g., wastewater discharge analyses)
6. Local, state, and federal reporting forms (e.g., hazardous waste manifests)
7. Local, state, and federal permits
8. Monthly utility billing records

How the data will be used

UT will collect inventory data and tally the inputs and outputs for the different solders. Information gathered by this form will be used to develop environmental profiles based on inputs and outputs for the manufacturing stage of the solders. The profiles will be used to evaluate environmental impacts from each product. The environmental profiles can be used to encourage product design changes for product improvement. UT will aggregate data and ensure that data associated with particular companies remain anonymous to the EPA. UT can enter into confidentiality agreements where proprietary data are concerned. Please understand that accurate and representative information from you is critical for the success of this project.

Results of project

The results are intended to provide industry with an analysis of the life-cycle environmental impacts and an analysis of end-of-life issues (e.g., recyclability and leachability) of leaded and lead-free solders. Results will help identify areas for product and process improvement as related to risk and environmental impact (e.g., identifying material use inefficiencies) and will identify impacts from various life-cycle stages of the solders. Use of the results will also help meet growing global demands of extended product responsibility.

Benefits of involvement

As a provider of data, you will be invited to be a member of the project's Technical Workgroup, which reviews interim project reports and is informed of on-going project status. This will allow for your interests to be considered in project development and data collection. By supplying data, the results will partially reflect your operations and, therefore, the results will be directly relevant to your interests. The project will allow you to directly apply results to your manufacturing process and identify areas for improvement and may directly affect industry selection of alterantive solders. You will also be recognized as working voluntarily and cooperatively with the U.S. EPA.

Deadline

The data collection time frame for this project is June 2002 to October 2002. Submission of forms are encouraged as soon as possible; however, we are attempting to obtain all completed forms before October 21, 2002.

Your cooperation and assistance are greatly appreciated.

*For any questions, please contact **Maria Leet Socolof at 865-974-9526** , <socolofml@utk.edu> or **Jack Geibig at 865-974-6513** , <jgiebig@utk.edu> at the University of Tennessee, 311 Conference Center Bldg., Knoxville, TN 37996-4134. Fax: 865-974-1838.*

For more project details, see < http://eerc.ra.utk.edu/ccpct/lfsp.html > and/or the Draft Final Goal Definition and Scoping Document.

INSTRUCTIONS

1. Please be sure to read the introductory text on each page before filling out the form.

2. The data you supply in the tables should represent inputs and outputs associated only with the **"product of interest" (i.e., a solder as defined in the introduction under Product Focus, and what you specify in Table 2, #1)**. If quantities provided are not specific to the "product of interest," please explain how they differ in the comments section at the bottom of the appropriate table. The ultimate goal is to quantify the amount of inputs and outputs per unit (e.g., kg) of solder manufactured.

3. Where supporting information is available as independent documents, reports or calculations, please provide them as attachments with reference to the associated table(s) in this form.

4. If you have more than one product of interest to this project, please duplicate this form and fill out one form for each product.

5. If there is not adequate room on a page to supply your data (including comments), please copy the appropriate page and attach it to this packet.

6. The ensuing pages refer to the following indices to detail specifics about the data. Additional information is provided below as required.
   Data Quality Indicators Index: These indicators will be used to assess the level of data quality in this form. Please report a DQI for the numerical value requested in each table on the following pages. The first category, **Measured**, pertains to a value that is a directly measured quantity. The second category, **Calculated**, refers to a value that required one or more calculations to obtain. The third category, **Estimated**, refers to a value that required a knowledgable employee's professional judgement to estimate. Lastly, the fourth category, **Assumed**, should be used only when a number had to be speculatively estimated.
   Hazardous and Nonhazardous Waste Management Methods Index: These methods are applicable to both hazardous and nonhazardous wastes (Tables 7a and 7b). Please give the appropriate abbreviation in the Management Method column on p. 7 where requested. Depending on whether the management method is on or offsite, please indicate by specifying "on" or "off" in the appropriate column on p. 7.

For Tables 3 - 6:

Data Quality Indicators Index	
M	- Measured
C	- Calculated
E	- Estimated
A	- Assumed

For Tables 6a and 6b:

Wastewater Treatment/Disposal Methods Index	
A	- Direct discharge to surface water
B	- Discharge to offsite wastewater treatment facility
C	- Underground injection
D	- Surface impoundment (e.g., settling pond)
E	- Direct discharge to land
F	- Other (please specify in comments section)

For Tables 7a and 7b (also provided on page 7):

Waste Management Methods Index	
RU	- Reused
R	- Recycled
L	- Landfilled
S	- Solidified/stabilized
Iv	- Incinerated - volume reduction
Ie	- Incinerated - energy conversion
D	- Deep well injected
O	- Other (please specify in comments section)

IF YOU HAVE QUESTIONS, PLEASE CONTACT EITHER:

Maria L. Socolof: Phone: 865-974-9526 Email: socolofml@utk.edu

OR

Jack Geibig: Phone: 865-974-3625 Email: jgeibig@utk.edu

1. FACILITY & CONTACT INFORMATION

Table 1.

Facility Information		Contact Information	
1. Company name:		4a. Prepared by:	Date:
2. Facility name:		4b. Title:	
3. Facility address (location):		4c. Phone number:	Ext.:
		4d. Fax number:	
		4e. Email address:	

5. Major products manufactured onsite and their % of your total production (by weight or volume--and please specify):

2. PRODUCT OF INTEREST INFORMATION

Table 2.

1. Solder of interest (please check one alloy, provide its composition, and complete the form for this alloy).
   Note, if more than one solder listed below is manufactured, please provide a separate form (Tables 2-7) for each solder of interest

☐ Sn/Pb	_____	☐ Sn/Ag/Cu	_____
☐ Sn/Cu	_____ [bar]	☐ Sn/Ag/Bi	_____ [paste]
		☐ Sn/Ag/Cu/Bi	_____ [paste]

2. Solder type (please check): ☐ **Bar** ☐ **Paste**

3. Solder density: _____

4. Solder melting point: _____

5. Annual production (past, current, or projected) (e.g., units, kg, lbs): _____

6. Year (or period of time) for which data are supplied (past, current, or projected): _____

7. Facility's percent global market share for solder of interest (optional): _____

8. Brief description of the main operations/subprocesses required to manufacture the product of interest: _____

9. From where (what countries) are your base metals supplied (company names optional) and what percent does each location contribute to your supply of each metal? _____

10. Please describe any recommended assembly profiles for your customers for this solder: _____

11. What % of your solder from your manufacturing process is recycled? _____ If recycled, (please check): ☐ **ON-SITE** ☐ **OFF-SITE**

a. If recycled on-site, how? _____

b. If recycled off-site, where? (please provide facility name and location if possible): _____

12. Do you accept customer's solder dross for recycling? ☐ **YES** ☐ **NO**

13. Do you accept back other contaminated waste forms specifically to recycle the solder? ☐ **YES** ☐ **NO** If so, what? _____

14. Have you conducted or do you have any leachability studies on the solder of interest? ☐ **YES** ☐ **NO** If yes, please provide a copy.

3. PRIMARY & ANCILLARY INPUTS

1. Primary & Ancillary Materials: Primary materials are defined as those materials that become part of the final product. Ancillary materials are those material inputs that assist production, yet do not become part of the final product (e.g., cleaning materials). Please include the trade name and the generic name of each material where applicable.
2. CAS # or MSDS: Please include either the CAS (Chemical Abstract Service) number of each material (fill in the blank with the number), or state "MSDS" and append a copy to this document.
3. Annual quantity/units & Density/units: Please specify the annual amount of material consumed in the year of interest (as specified in Table 2, #6). Please use the units of mass-per-year (e.g., kg/yr, lb/yr). If you specify units of volume in lieu of mass, please provide the density. If *annual* quantities are not available, provide applicable units (e.g., kg/1000 kg of product).
4. Data quality indicators: See the Data Quality Indicators Index on p. iii for abbreviations. Please supply the DQI for the *annual quantity* value given.
5. Recycled content: Please specify the recycled content of each material identified. For example, 60/40/0 would represent a material that has 60% virgin material, 40% pre-consumer recycled and 0% post-consumer recycled content. Enter N/A (not applicable) for all components that are assemblies.

Table 3a. **Primary Materials[1]**		**CAS # or MSDS[2]**	**Annual Quantity[3]**	**Units**	**Density[3]**	**Units**	**DQI[4]**	**Recycled Content[5]**
EXAMPLE: GRTX resin (polypropylene resin)		*MSDS*	*450,000*	*kg/yr*	-----	---	*M*	*60/40/0*
1.								
2.								
3.								
4.								
5.								
6.								
7.								

Primary material comments:

Table 3b. **Ancillary Materials[1]**		**CAS # or MSDS[2]**	**Annual Quantity[3]**	**Units**	**Density[3]**	**Units**	**DQI[4]**	**Recycled Content[5]**
EXAMPLE: Petroleum naphtha (cleaning solvent)		*8032-32-4*	*920*	*liters/yr*	*0.96*	*kg/liter*	*C*	*100/0/0*
1.								
2.								
3.								
4.								
5.								
6.								
7.								

Ancillary material comments:

4. UTILITY INPUTS

1. Annual quantity/units: Please specify the amount of the utility consumed in year of interest (as sepcified in Table 2, #6). If possible, please exclude nonprocess-related consumption. If this is not possible, please include a comment that nonprocess-related consumption is included. If *annual* quantities are not available, provide applicable units (e.g., kg/1000 kg of product).
2. Data quality indicators: See the Data Quality Indicators Index on p. iii for abbreviations. Please supply the DQI for the *annual quantity* value given.
3. Individual Utility Notes:

Electricity:

The quantity of electricity should reflect only that used toward manufacturing the product of interest (identified on p. 2). One approach would be to start with your facility's total annual electrical energy consumption, remove nonprocess-related consumption, then estimate what portion of the remaining consumption is related to the specific operations of interest. Please include consumption in all systems that use electricity for process-related purposes. Some examples include compressed air, chilled water, water deionization and HVAC consumption where clean or controlled environments are utilized.

Natural gas and LNG:

Please exclude all use for space heating or other nonprocess-related uses. If you choose to use units other than MCF (thousand cubic feet), please utilize only units of energy content or volume (e.g., mmBTU, therm, CCF).

Fuel oils:

Please use units of either volume or energy content (e.g., liters, mmBTU, MJ). Additionally, if the fuel oil is not delivered by underground pipeline, please include the associated transportation information.

All waters (e.g., DI, city):

Please include all waters received onsite. Please indicate consumption in units of mass or volume.

Table 4. Utilities[3]		**Annual Quantity[1]**	**Units**	**DQI[2]**
1.	Electricity		MJ	
2.	Natural gas		MCF	
3.	Liquified natural gas (LNG)		MCF	
4.	Fuel oil - type #2 (includes distillate and diesel)		liters	
5.	Fuel oil - type #4		liters	
6.	Fuel oil - type #6 (includes residual)		liters	
7.	Other petroleum-based fuel		liters	
8.	Water		liters	
9.				
10.				
11.				
12.				
13.				
Utility comments:				

5. AIR EMISSIONS

1. Air emissions: The emissions listed in the table below are some of the more common ones found in air release inventories; if you have information on other specific emissions, please provide them in the space provided. If you have any reporting forms or other air emission records for applicable year, please attach copies to this form. Also, if you have information on stack as well as fugitive emissions, please copy this page and place each set of emissions on a different page. The energy consumed in any equipment used onsite to treat air emissions should be included in the utilities values on p. 4.
2. Annual quantity/units: Please specify the amount of air emissions generated and released to the environment in the year of interest (as specified in Table 2, #6). If the emissions data are for a different year, please specify the year in the comments section below. Please use units of mass-per-year (e.g., kg/yr, lb/yr). If *annual* quantities are not available, provide applicable units (e.g., kg/1000 kg of product).
3. Data quality indicators: See the Data Quality Indicators Index on p. iii for abbreviations. Please supply the DQI for the *annual quantity* value given.

Table 5. Air Emissions[1]	**CAS number**	**Annual Quantity[2]**	**Units**	**DQI [3]**
Total particulates	-----			
Particulates < 10 microns (PM-10)	-----			
Sulfur oxides (SOx)	-----			
Nitrogen oxides (NOx)	-----			
Carbon monoxide	630-08-0			
Carbon dioxide	124-38-9			
Methane	74-82-8			
Benzene	71-43-2			
Toluene	108-88-3			
Xylenes	1330-20-7			
Naphthalene	91-20-3			
Total nonmethane VOCs	-----			
Other speciated hydrocarbon emissions:				
1.				
2.				
3.				
4.				
5.				
6.				
7.				
8.				
9.				
10.				
11.				

Table 5 (continued). **Air Emissions[1]**	**CAS number**	**Annual Quantity[2]**	**Units**	**DQI [3]**
Ammonia	7664-41-7			
Arsenic	7440-38-2			
Chromium	7440-47-3			
Copper	7440-50-8			
Lead	7439-92-1			
Manganese	7439-96-5			
Mercury	7439-98-7			
Nickel	7440-02-0			
Other emissions:				
1.				
2.				
3.				
4.				
5.				
6.				
7.				
8.				
9.				
10.				
11.				

Air emission comments:

6. WASTEWATER RELEASES & CONSTITUENTS

1. Annual quantity/units: Please specify the amount of wastewater(s) generated in the year of interest (as specified in Table 2, #6). Please use units of mass-per-year (e.g., kg/yr, lb/yr). If multiple streams exist, please copy this page and fill it out for each stream. If *annual* quantities are not available, provide applicable units (e.g., kg/1000 kg of product).
2. Data quality indicators: See the Data Quality Indicators Index on p. iii for abbreviations. Please include one DQI for the annual wastewater stream quantity value supplied, and one DQI for the wastewater constituents information supplied. If more than one DQI is applicable to the wastewater constituents data, please clarify this in the comment section.
3. Wastewater constituents: Please let us know what type of values you are supplying (e.g., daily maximums, monthly averages, annual averages). Additionally, if you have any reporting forms of other wastewater constituent records for the year of interest, please attach them to this form. The energy consumed in any equipment used onsite to treat wastewater releases should be included in the utilities values on p. 4.
4. Concentration/units: Please specify the concentration of wastewater constituents generated in the year of interest. Please use units of mass-per-volume (e.g., mg/liter, lb/gal).
5. Wastewater treatment/disposal method: See the Wastewater Treatment/Disposal Methods Index on p. iii for method abbreviations.

Table 6a. Wastewater Stream	**Annual Quantity[1]**	**Units**	**Treatment/Disposal Method[5]**	**DQI for Annual Quantity**	**DQI for Constituents below**

Table 6b. Wastewater Constituents[3]	**CAS number**	**Concentration[4]**	**Units**
Dissolved solids	-----		
Suspended solids	-----		
Carbonaceous Oxygen Demand (COD)	-----		
Biological Oxygen Demand (BOD)	-----		
Oil & grease	-----		
Hydrochloric acid	7647-01-0		
Sulfuric acid	7664-93-9		
Other acids (please specify):			
1.			
2.			
Phosphorus			
Phosphates			
Sulfates			
Fluorides			
Cyanide			
Chloride			
Chromium			
Aluminum			
Nickel			

Table 6b (continued). **Wastewater Constituents[3]**	**CAS number**	**Concentration[4]**	**Units**
Mercury			
Lead			
Nitrogen			
Zinc			
Tin			
Ferrous sulfate			
Ammonia			
Nitrates			
Pesticides			
Other speciated constituents:			
1.			
2.			
3.			
4.			
5.			
6.			
Wastewater comments:			

7. HAZARDOUS & NONHAZARDOUS WASTES

1. Hazardous wastes and EPA hazardous waste numbers: Please list your waste streams that are considered hazardous by the U.S. EPA. Include the hazardous waste codes for any hazardous waste you include.
2. Annual quantity/units & Density/units: Please specify the amount of waste generated in the year of interest (as specified in Table 2, #6). Use units of mass-per-year (e.g., kg/yr, lb/yr). Please also provide the density for each waste. If *annual* quantities are not available, provide applicable units (e.g., kg/1000 kg of product).
3. Data quality indicators: See the Data Quality Indicators Index on p. iii for abbreviations. Please supply the DQI for the *annual quantity* value given.
4. Management method: See key to right of tables for Management Methods Index. If none are applicable, please indicate other and use the comments section to expound.

Table 7a. Hazardous Wastes[1]	**EPA Haz. Waste #[1]**	**Annual Quantity[2]**	**Units**	**Density[2]**	**Units**	**DQI[3]**	**Mgmt. method[4]**	**On or offsite?**
EXAMPLE: Spent solvent (toluene)	*F005*	*20,000*	*kg/yr*	*0.9*	*kg/liter*	*M*	*Ie*	*off*
1.								
2.								
3.								
4.								
5.								
6.								
7.								
8.								

Hazardous waste comments:

Table 7b. Nonhazardous Wastes	**Annual Quantity[2]**	**Units**	**Density[2]**	**Units**	**DQI[3]**	**Mgmt. method[4]**	**On or offsite?**
EXAMPLE: Waste metal chips	*22,000*	*kg/yr*	*1,000*	*kg/m3*	*C*	*R*	*off*
1.							
2.							
3.							
4.							
5.							
6.							
7.							

Nonhazardous waste comments:

Management Methods Index	
RU	Reused
R	Recycled
L	Landfilled
S	Solidified/stabilized
Iv	Incinerated-volume reduction
Ie	Incinerated-energy conversion
D	Deep well injected
O	Other (specify in comments)

DESIGN FOR THE ENVIRONMENT
LEAD-FREE SOLDER PROJECT

Life-Cycle Inventory (LCI) Data Collection Form
For Solder Recycling Operations

Introduction

The Design for the Environment (DfE) Program in the U.S. Environmental Protection Agency's (EPA) Office of Pollution Prevention and Toxics has begun a voluntary, cooperative project with the electronics industry to assess the life-cycle environmental impacts of solder alternatives. The DfE Program conducts comparative analyses of alternative products or processes to provide businesses with data to make environmentally informed choices about product or process improvements. The DfE Program has no regulatory or enforcement agenda and was established to act as a partner with industry to promote pollution prevention. This environmental life-cycle assessment will address human and environmental impacts (e.g., energy, natural resource use, global warming, chronic toxicity) of various solders. The University of Tennessee (UT) Center for Clean Products and Clean Technologies is conducting the life-cycle inventory (LCI), which is the data collection phase of a life-cycle assessment, with technical assistance from IPC -- Association Connecting Electronics Industries, the Electronic Industries Alliance (EIA), and other partners.

Boundaries

A life-cycle assessment considers impacts from materials acquisition, material manufacturing, product manufacturing, use, and final disposition of a product. The LCI data are intended to be used to evaluate relative environmental impacts over the entire life-cycle of a product. In this project, the product is a type of solder. Therefore, data associated with the materials and processes used directly in the manufacturing, use, and disposition of the product are relevant to the LCI and requested in this form. You will not need to include materials or energy not directly used in the production of the solder (e.g., general building heating and air conditioning).

Product focus

This project will evaluate tin-lead solder (for wave and reflow operations) and consider the following lead-free alternatives:

-- Sn/Cu (wave)
-- Sn/Ag/Cu (wave and reflow)
-- Sn/Ag/Bi or Sn/Ag/Cu/Bi (reflow)

Most recent production data are desired (2001 or 2002).

Inventory data

We are asking for data on one or multiple "product(s) of interest" that you manufacture, which may be one as defined above under Product Focus. The inputs and outputs data (Fig. 1) that you provide will be aggregated in the LCI to quantify the overall inputs and outputs of a solder alternative over its life-cycle. A separate form should be completed for each different type of solder of interest recycled.

Data sources

Much of the requested information can be drawn from existing sources, including, but not limited to the following:

1. Purchase and production records
2. Bills and invoices
3. Material Safety Data Sheets (MSDS)
4. Toxic Release Inventory (TRI) forms
5. Audit and analysis results (e.g., wastewater discharge analyses)
6. Local, state, and federal reporting forms (e.g., hazardous waste manifests)
7. Local, state, and federal permits
8. Monthly utility billing records

How the data will be used

UT will collect inventory data and tally the inputs and outputs for the different solders. Information gathered by this form will be used to develop environmental profiles based on inputs and outputs for the end-of-life stage of the solders. The profiles will be used to evaluate environmental impacts from each product. The environmental profiles can be used to encourage product design changes for product improvement. UT will aggregate data and ensure that data associated with particular companies remain anonymous to the EPA. UT can enter into confidentiality agreements where proprietary data are concerned. Please understand that accurate and representative information from you is critical for the success of this project.

Results of project

The results are intended to provide industry with an analysis of the life-cycle environmental impacts and an analysis of end-of-life issues (e.g., recyclability and leachability) of leaded and lead-free solders. Results will help identify areas for product and process improvement as related to risk and environmental impact (e.g., identifying material use inefficiencies) and will identify impacts from various life-cycle stages of the solders. Use of the results will also help meet growing global demands of extended product responsibility.

Benefits of involvement

As a provider of data, you will be invited to be a member of the project's Technical Workgroup , which reviews interim project reports and is informed of on-going project status. This will allow for your interests to be considered in project development and data collection. By supplying data, the results will partially reflect your operations and, therefore, the results will be directly relevant to your interests. The project will allow you to directly apply results to your manufacturing process and identify areas for improvement and may directly affect industry selection of alternative solders. You will also be recognized as working voluntarily and cooperatively with the U.S. EPA.

Deadline

The data collection time frame for this project is May 2002 to November 2002. Submission of forms are encouraged as soon as possible; however, we are attempting to obtain all completed forms before October 21, 2002.

Your cooperation and assistance are greatly appreciated.

For any questions, please contact ***Maria Leet Socolof at 865-974-9526*** *, <socolofml@utk.edu> or* ***Jack Geibig at 865-974-6513*** *, <jgiebig@utk.edu> at the University of Tennessee, 311 Conference Center Bldg., Knoxville, TN 37996-4134. Fax: 865-974-1838.*

For more project details, see the Project Fact Sheet, DfE Website < www.epa.gov/dfe >, or the Draft Final Goal Definition and Scoping Document.

INSTRUCTIONS

1. Please be sure to read the introductory text on each page before filling out the form.

2. The data you supply in the tables should represent inputs and outputs associated only with the **"product of interest" (i.e., a solder as defined in the introduction under Product Focus, and what you specify in Table 2, #1)**. If quantities provided are not specific to the "product of interest," please explain how they differ in the comments section at the bottom of the appropriate table.

3. Where supporting information is available as independent documents, reports or calculations, please provide them as attachments with reference to the associated table(s) in this form.

4. If you have more than one product of interest to this project, please duplicate this form and fill out one form for each product.

5. If there is not adequate room on a page to supply your data (including comments), please copy the appropriate page and attach it to this packet.

6. The ensuing pages refer to the following indices to detail specifics about the data. Additional information is provided below as required.
   Data Quality Indicators Index: These indicators will be used to assess the level of data quality in this form. Please report a DQI for the numerical value requested in each table on the following pages. The first category, **Measured**, pertains to a value that is a directly measured quantity. The second category, **Calculated**, refers to value that required one or more calculations to obtain. The third category, **Estimated**, refers to a value that required a knowledgable employee's professional judgement to estimate. Lastly, the fourth category, **Assumed**, should be used only when a number had to be speculatively estimated.
   Hazardous and Nonhazardous Waste Management Methods Index: These methods are applicable to both hazardous and nonhazardous wastes (Tables 7a and 7b). Please give the appropriate abbreviation in the Management Method column on p. 7 where requested. Depending on whether the management method is on or offsite, please indicate by specifying "on" or "off" in the appropriate column on p. 7.

For Tables 3 - 6:

Data Quality Indicators Index	
M	- Measured
C	- Calculated
E	- Estimated
A	- Assumed

For Tables 6a and 6b:

Wastewater Treatment/Disposal Methods Index	
A	- Direct discharge to surface water
B	- Discharge to offsite wastewater treatment facility
C	- Underground injection
D	- Surface impoundment (e.g., settling pond)
E	- Direct discharge to land
F	- Other (please specify in comments section)

For Tables 7a and 7b (also provided on page 7):

Waste Management Methods Index	
RU	- Reused
R	- Recycled
L	- Landfilled
S	- Solidified/stabilized
Iv	- Incinerated - volume reduction
Ie	- Incinerated - energy conversion
D	- Deep well injected
O	- Other (please specify in comments section)

IF YOU HAVE QUESTIONS, PLEASE CONTACT EITHER:

Maria L. Socolof: Phone: 865-974-9526 Email: socolofml@utk.edu

OR

Jack Geibig: Phone: 865-974-3625 Email: jgeibig@utk.edu

1. FACILITY & CONTACT INFORMATION

Table 1.	Facility Information	Contact Information	
1. Company/Facility name:		4a. Prepared by:	Date:
2. Facility address (location):		4b. Title:	
		4c. Phone number:	Ext.:
		4d. Fax number:	
		4e. Email address:	
3. Products produced onsite (e.g., secondary lead, recycled Sn/Pb):			

2. PRODUCT OF INTEREST INFORMATION

Table 2.

NOTE: If more than one solder listed in #3 is processed, please provide a separate form for each alloy, if possible

1. What is your major recycled product (e.g., lead, tin, copper)? _____

2. Do you accept: ☐ post industrial waste (e.g., dross from printed wiring board assemblers)

   ☐ post consumer waste (e.g., printed wiring boards from disassembled consumer products)

3. What waste solder alloys do you recieve for recycling [check the applicable alloy(s) and provide composition]:

   ☐ Sn/Pb _____ ☐ Sn/Ag/Cu _____

   ☐ Sn/Cu _____ ☐ Sn/Ag/Bi _____

   ☐ Sn/Ag/Cu/Bi _____

4. What is your annual production of recycled solder metal (past, current, or projected) (e.g., units, kg, lbs).
   Specify each solder metal that is recycled and the production associated with each metal: _____

5. What percent of your operations are associated with processing electronics scrap only? _____

6. Year (or period of time) for which data are supplied (past, current, or projected): _____

7. Facility's percent global market share for solder of interest (optional): _____

8. Briefly describe the main operations/subprocesses required to process the waste solder: _____

9. What by-products are produced?

10. If you are processing lead-free solders in your recycling operations, briefly describe how operations differ from processing Sn-Pb (e.g., greater energy demands, greater time, more refining steps): Note, if you are processing lead-free solders separately, please provide all separate tables in this form for each different alloy processed.

3. PRIMARY & ANCILLARY INPUTS

Data for_____ alloy

1. Primary & Ancillary Materials: Primary materials are defined as those materials that become part of the final product. Ancillary materials are those material inputs that assist production, yet do not become part of the final product (e.g., cleaning materials). Please include the trade name and the generic name of each material where applicable.
2. CAS # or MSDS: Please include either the CAS (Chemical Abstract Service) number of each material (fill in the blank with the number), or state "MSDS" and append a copy to this document.
3. Annual quantity/units & Density/units: Please specify the annual amount of material consumed in the year of interest (as specified in Table 2, #6). Please use the units of mass-per-year (e.g., kg/yr, lb/yr). If you specify units of volume in lieu of mass, please provide the density. If *annual* quantities are not available, provide applicable units (e.g., kg/1000 kg of product).
4. Data quality indicators: See the Data Quality Indicators Index on p. iii for abbreviations. Please supply the DQI for the *annual quantity* value given.
5. Recycled content: Please specify the recycled content of each material identified. For example, 60/40/0 would represent a material that has 60% virgin material, 40% pre-consumer recycled and 0% post-consumer recycled content. Enter N/A (not applicable) for all components that are assemblies.

Table 3a. Primary Materials[1]	**CAS # or MSDS[2]**	**Annual Quantity[3]**	**Units**	**Density[3]**	**Units**	**DQI[4]**	**Recycled Content[5]**
EXAMPLE: GRTX resin (polypropylene resin)	*MSDS*	*450,000*	*kg/yr*	-----	---	*M*	*60/40/0*
1.							
2.							
3.							
4.							
5.							
6.							
7.							

Primary material comments:

Table 3b. Ancillary Materials[1]	**CAS # or MSDS[2]**	**Annual Quantity[3]**	**Units**	**Density[3]**	**Units**	**DQI[4]**	**Recycled Content[5]**
EXAMPLE: Petroleum naphtha (cleaning solvent)	*8032-32-4*	*920*	*liters/yr*	*0.96*	*kg/liter*	*C*	*100/0/0*
1.							
2.							
3.							
4.							
5.							
6.							
7.							

Ancillary material comments:

4. UTILITY INPUTS

Data for _____ alloy

1. Annual quantity/units: Please specify the amount of the utility consumed in year of interest (as sepcified in Table 2, #6). If possible, please exclude nonprocess-related consumption. If this is not possible, please include a comment that nonprocess-related consumption is included. If *annual* quantities are not available, provide applicable units (e.g., kg/1000 kg of product).
2. Data quality indicators: See the Data Quality Indicators Index on p. iii for abbreviations. Please supply the DQI for the *annual quantity* value given.
3. Individual Utility Notes:

Electricity:

The quantity of electricity should reflect only that used toward manufacturing the product of interest (identified on p. 2). One approach would be to start with your facility's total annual electrical energy consumption, remove nonprocess-related consumption, then estimate what portion of the remaining consumption is related to the specific operations of interest. Please include consumption in all systems that use electricity for process-related purposes. Some examples include compressed air, chilled water, water deionization and HVAC consumption where clean or controlled environments are utilized.

Natural gas and LNG:

Please exclude all use for space heating or other nonprocess-related uses. If you choose to use units other than MCF (thousand cubic feet), please utilize only units of energy content or volume (e.g., mmBTU, therm, CCF).

Fuel oils:

Please use units of either volume or energy content (e.g., liters, mmBTU, MJ). Additionally, if the fuel oil is not delivered by underground pipeline, please include the associated transportation information.

All waters (e.g., DI, city):

Please include all waters received onsite. Please indicate consumption in units of mass or volume.

Table 4.	**Utilities[3]**	**Annual Quantity[1]**	**Units**	**DQI[2]**
1.	Electricity		MJ	
2.	Natural gas		MCF	
3.	Liquified natural gas (LNG)		MCF	
4.	Fuel oil - type #2 (includes distillate and diesel)		liters	
5.	Fuel oil - type #4		liters	
6.	Fuel oil - type #6 (includes residual)		liters	
7.	Other petroleum-based fuel		liters	
8.	Water		liters	
9.				
10.				
11.				
12.				
13.				

Utility comments:

5. AIR EMISSIONS

Data for _____ alloy

1. Air emissions: The emissions listed in the table below are some of the more common ones found in air release inventories; if you have information on other specific emissions, please provide them in the space provided. If you have any reporting forms or other air emission records for applicable year, please attach copies to this form. Also, if you have information on stack as well as fugitive emissions, please copy this page and place each set of emissions on a different page. The energy consumed in any equipment used onsite to trea t air emissions should be included in the utilities values on p. 4.
2. Annual quantity/units: Please specify the amount of air emissions generated and released to the environment in the year of interest (as specified in Table 2, #6). If the emissions data are for a different year, please specify the year in the comments section below. Please use units of mass-per-year (e.g., kg/yr, lb/yr). If *annual* quantities are not available, provide applicable units (e.g., kg/1000 kg of product).
3. Data quality indicators: See the Data Quality Indicators Index on p. iii for abbreviations. Please supply the DQI for the *annual quantity* value given.

Table 5. Air Emissions[1]	**CAS number**	**Annual Quantity[2]**	**Units**	**DQI[3]**
Total particulates	-----			
Particulates < 10 microns (PM-10)	-----			
Sulfur oxides (SOx)	-----			
Nitrogen oxides (NOx)	-----			
Carbon monoxide	630-08-0			
Carbon dioxide	124-38-9			
Methane	74-82-8			
Benzene	71-43-2			
Toluene	108-88-3			
Xylenes	1330-20-7			
Naphthalene	91-20-3			
Total nonmethane VOCs	-----			
Other speciated hydrocarbon emissions:				
1.				
2.				
3.				
4.				
5.				
6.				
7.				
8.				
9.				
10.				
11.				

Table 5 (continued). **Air Emissions[1]**	**CAS number**	**Annual Quantity[2]**	**Units**	**DQI[3]**
Ammonia	7664-41-7			
Arsenic	7440-38-2			
Chromium	7440-47-3			
Copper	7440-50-8			
Lead	7439-92-1			
Manganese	7439-96-5			
Mercury	7439-98-7			
Nickel	7440-02-0			
Other emissions:				
1.				
2.				
3.				
4.				
5.				
6.				
7.				
8.				
9.				
10.				
11.				

Air emission comments:

6. WASTEWATER RELEASES & CONSTITUENTS

Data for _____ alloy

1. Annual quantity/units: Please specify the amount of wastewater(s) generated in the year of interest (as specified in Table 2, #6). Please use units of mass-per-year (e.g., kg/yr, lb/yr). If multiple streams exist, please copy this page and fill it out for each stream. If *annual* quantities are not available, provide applicable units (e.g., kg/1000 kg of product).
2. Data quality indicators: See the Data Quality Indicators Index on p. iii for abbreviations. Please include one DQI for the annual wastewater stream quantity value supplied, and one DQI for the wastewater constituents information supplied. If more than one DQI is applicable to the wastewater constituents data, please clarify this in the comment section.
3. Wastewater constituents: Please let us know what type of values you are supplying (e.g., daily maximums, monthly averages, annual averages). Additionally, if you have any reporting forms of other wastewater constituent records for the year of interest, please attach them to this form. The energy consumed in any equipment used onsite to treat wastewater releases should be included in the utilities values on p. 4.
4. Concentration/units: Please specify the concentration of wastewater constituents generated in the year of interest. Please use units of mass-per-volume (e.g., mg/liter, lb/gal).
5. Wastewater treatment/disposal method: See the Wastewater Treatment/Disposal Methods Index on p. iii for method abbreviations.

Table 6a. Wastewater Stream	**Annual Quantity[1]**	**Units**	**Treatment/Disposal Method[5]**	**DQI for Annual Quantity**	**DQI for Constituents below**

Table 6b. Wastewater Constituents[3]	**CAS number**	**Concentration[4]**	**Units**
Dissolved solids	-----		
Suspended solids	-----		
Carbonaceous Oxygen Demand (COD)	-----		
Biological Oxygen Demand (BOD)	-----		
Oil & grease	-----		
Hydrochloric acid	7647-01-0		
Sulfuric acid	7664-93-9		
Other acids (please specify):			
1.			
2.			
Phosphorus			
Phosphates			
Sulfates			
Fluorides			
Cyanide			
Chloride			
Chromium			
Aluminum			
Nickel			

Table 6b (continued). **Wastewater Constituents[3]**	**CAS number**	**Concentration[4]**	**Units**
Mercury			
Lead			
Nitrogen			
Zinc			
Tin			
Ferrous sulfate			
Ammonia			
Nitrates			
Pesticides			
Other speciated constituents:			
1.			
2.			
3.			
4.			
5.			
6.			
Wastewater comments:			

7. HAZARDOUS & NONHAZARDOUS WASTES

Data for _____ alloy

1. Hazardous wastes and EPA hazardous waste numbers: Please list your waste streams that are considered hazardous by the U.S. EPA. Include the hazardous waste codes for any hazardous waste you include.
2. Annual quantity/units & Density/units: Please specify the amount of waste generated in the year of interest (as specified in Table 2, #6). Use units of mass-per-year (e.g., kg/yr, lb/yr). Please also provide the density for each waste. If *annual* quantities are not available, provide applicable units (e.g., kg/1000 kg of product).
3. Data quality indicators: See the Data Quality Indicators Index on p. iii for abbreviations. Please supply the DQI for the *annual quantity* value given.
4. Management method: See key to right of tables for Management Methods Index. If none are applicable, please indicate other and use the comments section to expound.

Table 7a. Hazardous Wastes[1]	**EPA Haz. Waste #[1]**	**Annual Quantity[2]**	**Units**	**Density[2]**	**Units**	**DQI[3]**	**Mgmt. method[4]**	**On or offsite?**
EXAMPLE: Spent solvent (toluene)	*F005*	*20,000*	*kg/yr*	*0.9*	*kg/liter*	*M*	*Ie*	*off*
1.								
2.								
3.								
4.								
5.								
6.								
7.								
8.								

Hazardous waste comments:

Management Methods Index	
RU	Reused
R	Recycled
L	Landfilled
S	Solidified/stabilized
Iv	Incinerated-volume reduction
Ie	Incinerated-energy conversion
D	Deep well injected
O	Other (specify in comments)

Table 7b. nhazardous Wastes	**Annual Quantity[2]**	**Units**	**Density[2]**	**Units**	**DQI[3]**	**Mgmt. method[4]**	**On or offsite?**
EXAMPLE: Waste metal chips	*22,000*	*kg/yr*	*1,000*	*kg/m3*	*C*	*R*	*off*
1.							
2.							
3.							
4.							
5.							
6.							
7.							

Nonhazardous waste comments:

APPENDIX B:
USE/APPLICATION ENERGY TESTING

- Geibig, J., M. Socolof, P. Paulraj, and T. Brady. "Life-Cycle Impacts of Energy Consumption during Reflow Assembly of Electronics using Lead-Free Solders," IPC APEX 2003, Anaheim, California.

Life-Cycle Impacts of Energy Consumption during Reflow Assembly of Electronics Using Lead-Free Solders

Jack Geibig
University of Tennessee
Knoxville, TN
Jgeibig@utk.edu

Maria Socolof
University of Tennessee
Knoxville, TN
Msoc@utk.edu

Prawin Paulraj
Intel Corporation
Hillsboro, OR
Prawin.paulraj@intel.com

Todd Brady
Intel Corporation
Chandler, AZ
Todd.a.brady@intel.com

Abstract— The energy consumed during the reflow assembly of printed wiring board assemblies is expected to be environmentally significant within the solder product life-cycle. Wide differences in the melting temperatures of lead and lead-free solders alternatives suggests that there may be large and important tradeoffs associated with the selection of solder and its ultimate impact on the environment. Preliminary results of testing, conducted as part of an overall life-cycle assessment of lead and lead free solders, are presented in this paper and then compared to previously conducted studies. Life-cycle impacts associated the test data are also presented.

Testing results indicate that energy consumption can vary by as much as 40 percent across alternative solders, with the National Electronics Manufacturing Initiative (NEMI) recommended Sn/Ag/Cu alloy consuming eight percent more energy than eutectic Sn/Pb, and the Sn/Ag/Bi alloy consuming as much as 32 percent less energy. Although absolute energy consumption values during this test were higher than other studies, relative energy differences between solder types strongly agreed with those of previous studies. Finally, the environmental impacts associated with the energy consumed during reflow assembly were demonstrated to be significant when compared energy use in upstream life-cycle processes.

INTRODUCTION

Adoption of lead-free solders for the manufacturing of electronics presents the industry with many challenges. One such challenge results from the elevated melting points of the leading solder alternatives and the changes required in the associated assembly profiles. More energy is likely required to maintain the higher oven temperatures required to melt and then reflow these solders during assembly, resulting in increased costs to assemblers and potential environmental impacts [1, 2].

The University of Tennessee has partnered with the US EPA Design for the Environment Program, non-government organizations, and members of the electronics industry to evaluate the life-cycle environmental and human health impacts of lead and lead-free solder use in the electronics industry. The primary goal of the project is to conduct a detailed life-cycle assessment (LCA) of leading solder alternatives that considers the impacts associated with the entire product system. For solder, the product system life-cycle stages include materials extraction and processing of the metal ore, manufacturing of the solder, application of the solder during assembly, and the final disposition of the solder as part of waste electronics.

Primary life-cycle impacts occurring during the solder application life-cycle stage are expected to result from the energy consumed during the reflow assembly process [2, 3]. To assess the environmental consequences of a change in solders during reflow, project partners conducted testing at an Intel facility to estimate the energy consumed during the reflow assembly of printed wiring boards (PWBs) using select lead and lead-free solders. This paper presents the findings of the testing and compares the results to the energy consumed from other upstream life-cycle processes.

SOLDER REFLOW TEST METHODOLOGY

Development of a testing protocol was performed in cooperation with a group of industry experts knowledgeable about reflow assembly as well as the overall goals of the LCA project. The advisory group included representatives from solder suppliers, equipment manufacturers, and electronics manufacturers with in-house assembly capability. The developed protocol balanced the need to collect data in a timely and cost efficient manner with the desire to capture the primary factors of power consumption during assembly; namely, the shape of the oven temperature profile, conveyor speed, oven loading, and the overall mass of the printed wiring board (PWB) assembly. In order to evaluate the power consumption under typical operating conditions, it was assumed that the ovens would be operating continuously throughout the day or that work would be scheduled to minimize cost of operation. Therefore, testing was confined to the measurement of power consumption during periods of steady-state

operation, neglecting the preheat cycle.

Solders for evaluation were selected with the overall objectives of the LCA study in mind, and include the solders selected for evaluation in the larger LCA study. Solder alloys compositions evaluated during the testing include:

- Sn/Pb - 63/37
- Sn/Ag/Bi (SAB) - 42/1/57
- Sn/Ag/Cu (SAC) - 95.5/3.9/0.6

As a result of prior testing at Intel, assembly profiles describing the rate and duration of the incremental temperature changes the assembly must undergo to obtain a functioning solder joint were already available for all but the bismuth-containing solder. A suggested profile for the bismuth-containing solder was obtained from Hewlett Packard and used by Intel to develop an appropriate reflow profile. The suggested profile was adjusted using a set of thermocouples attached to the surface of the panel. The panel was then passed repeatedly through the temperature zones of the reflow oven while the profile was adjusted until the surface temperature of the panel met the minimum peak melting temperature of the solder. The resulting profile for each solder is depicted in Figure 1.

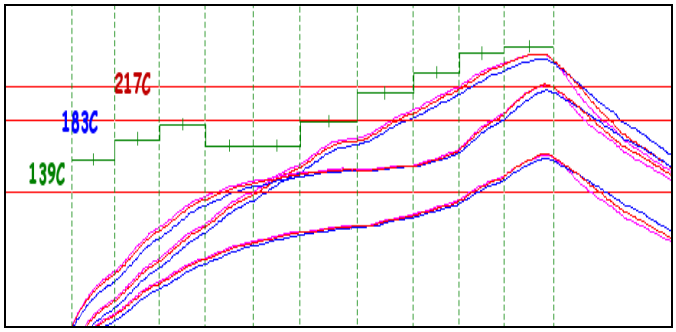


Figure 1. Solder Reflow Profiles

For comparison purposes, each profile was developed using a constant conveyor speed across profiles to ensure a constant and comparable oven loading during periods of energy measurement. Characteristics of the solder profiles are presented in Table 1.

Table 1. Reflow Profile Specifications

Solder	Peak Temperature (range)	TAL (average)	δ Temp
Sn/Ag/Bi	160.2-170.1C	65 secs	9.9C
Sn/Pb	204.4-219.1C	51 secs	14.7C
Sn/Ag/Cu	235.2-248.8C	65 secs	13.6C

An Intel micro ATX motherboard that had been previously assembled was selected as the test assembly for this testing. The motherboard was selected as a baseline for testing because it is at the upper end of applications typical for the consumer electronics market in terms of size, mass and complexity.

Because solder reflow occurs once the joint reaches the minimus temperature required for the particular solder, and because the scope of our testing was limited to energy consumption and not joint testing, preassembled boards were used to limit the cost of the testing. A photo of the test board is shown in Figure 2. Specifications for the test assembly are presented in Table 2.

Figure 2. Reflow test PWB assembly

Table 2. Test Vehicle Specifications

PWB Type	Micro ATX Motherboard
Length	9.6 inches
Width	9.6 inches
Mass of Assembly	225 grams
Mass of Solder (estimated)	2.5 grams/board

Testing was conducted at the Intel facility in Hillsboro, Oregon using a ten zone forced convection reflow oven with an attached water-cooled chiller unit to cool the assemblies following reflow. Energy measurements were taken at the main power feeds to both the oven and chiller using appropriately sized transducers and a data logger. Assemblies were fed into the oven at a controlled rate of 35.5 inches per minute until the oven achieved a fully loaded condition under the design profile. Energy measurements were taken from the time the first assembly entered the oven until the final assembly exited the chiller, a test run duration of thirteen minutes. Assemblies exiting the oven were allowed to reach room temperature before being reintroduced to the oven for the next test run.

TESTING RESULTS

Results from the reflow testing are presented in Table 3 below, along with the results from a similar study conducted by the National Electronics Manufacturing Initiative (NEMI) [4].

Table 3. Energy Consumption during Reflow Testing

Solder	UT/ Intel (kW)	% Change from Baseline	NEMI (kW)	% Change from Baseline
Sn/Ag/Bi	15.7	-32.5	N/A	---

Sn/Pb	23.3	---	14.8	---
Sn/Ag/Cu	25.2	8.3	16.5	11.5%

Testing results indicate that there are significant differences in the amounts of energy required to reflow the various solders under our test conditions. For example, as compared to eutectic Sn/Pb solder, the SAC alloy consumed 8.3 percent more energy over the same period of process operation. This is mostly due to the elevated melting point (218 ^{o}C) of the SAC alloy, which is a full 35 ^{o}C higher than that of the eutectic Sn/Pb alloy. The increased temperature not only results in higher energy consumption during reflow, but also requires the re-engineering of most PWB surface components which can fail under the higher temperature reflow cycle.

By contrast, the SAB alloy consumed nearly 33 percent less energy over the same test period. This is largely due to the influence of the high concentration of bismuth in the solder that acts to reduce the overall melting point of the alloy to 138 ^{o}C, a full 45 ^{o}C less than the melting point for the Sn/Pb eutectic. Still, the results relative to the other solders are somewhat lower than can be attributed simply to the decreased melting point. The larger decrease may also involve other factors such as higher oven efficiency at the lower temperature, and less energy loss from the oven due to PWB throughput. In addition, the peak reflow temperature of 179 ^{o}C for the high bismuth alloy does not approach the typical reflow temperatures used for Sn/Pb, making the full range of currently approved components available for assembly without concern for increased component failure rates.

Results from similar testing conducted as part of the research activities of the NEMI Lead-Free Component team have also been displayed in Table 4 for comparison purposes. As shown in the table, the data presented in this paper are higher than those reported by the NEMI group [4]. Other studies, both published and unpublished confirm this disparity [5, 6, 7]. However, while the absolute energy values are higher, the relative energy consumption among the different solder alloys reported in this work agrees very well with that of the other studies. At the time of this writing, the authors are investigating the source of disparity between the reported data sets, but are uncertain as to the cause due to our unfamiliarity with the other studies. Possible sources of disparity may include the use of less efficient, older reflow equipment, testing protocols, and differences in the conditions under which testing occurred (e.g. reflow profiles). The NEMI study did not include the SAB alloy so no comparison can be made to the data collected in this study for that alloy.

An attempt was made to characterize the magnitude of energy loss to the system attributable to the mass of PWB assembly passing through the reflow zone. This 'heat sink' affect is not solely attributable to the mass of the solder, but rather is related to the mass of the overall assemblies and the individual characteristics of the materials involved. By comparing the energy consumption of the reflow ovens under loaded and unloaded conditions, the amount of additional energy required due to the work being passed through the system is estimated and presented in Table 4 below.

Table 4. Baseline Reflow Oven Power Consumption

Solder	Unloaded (kW)	Loaded (kW)	% of Total Energy Due to Loading
Sn/Ag/Bi	15	15.7	4.5
Sn/Pb	20.9	23.3	10.3
Sn/Ag/Cu	22.2	25.2	11.9

These results apply only to the PWB assembly used in this testing. However, they also provide a snapshot against which other board designs and configurations may be compared to assess the potential magnitude of their respective energy consumption and the potential range of values possible.

LIFE CYCLE COMPARISON

Results from the energy consumption testing reported in the previous section were combined with energy data collected from other life-cycle stages to assess the impacts of energy use within the product life-cycle. Sources of energy included in this evaluation were electricity from the US power grid, heavy fuel oil, and natural gas. Energy values within each life-cycle stage were converted to a common value of megajoules (MJ) and then combined to obtain an energy use for the entire life-cycle stage. To facilitate comparison of the energy use across life-cycle stages and for different solders, a functional unit based on the volume of solder was used to normalize all data. The volumes were converted to mass using the density of the solder alloys, and all data adjusted and reported in energy use per mass of solder processed.

Life-cycle impacts resulting from energy use were calculated and presented for the materials extraction & processing (e.g. diesel to power mining equipment), solder manufacturing (e.g. natural gas to fire the refining pots), and solder application life-cycle stages. Since end-of-life (EOL) energy use data (e.g. electricity to power shredders) are not yet completely collected and aggregated, impacts from end-of-life were not included in this evaluation. The resulting data by life-cycle stage for each solder are presented in Figure 3.

The figure shows that the energy consumed during the application and assembly of the PWB's dominate, with results ranging from ranging from 91-96 percent of the overall life-cycle energy, depending on the solder type. Unlike with the other life-cycle stages where the energy consumption is tightly linked to the mass of solder

produced, the energy consumed during the reflow application stage is a function of the physical characteristics of the solder alloy, and only minutely affected by the mass of solder processed. The differences in energy consumption between life-cycle stages become magnified after the data are normalized by the mass of solder produced.

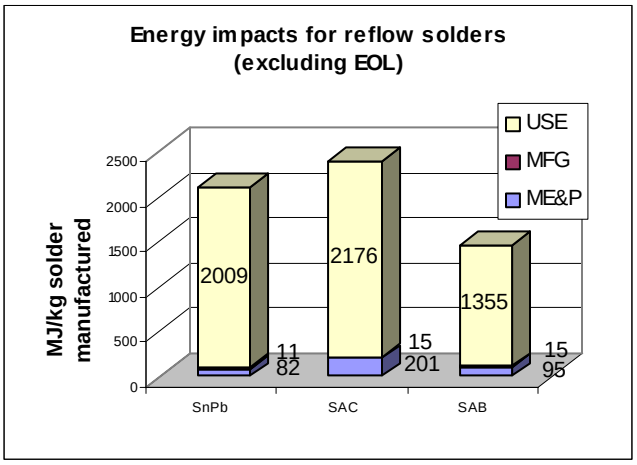


Figure 3. Life-Cycle Energy Use (excluding EOL)

Our testing found a higher rate of energy use during reflow than other reported data. For purposes of comparison, the NEMI data were substituted for the project test data and the life-cycle energy use was recalculated. The results are shown in Figure 4.

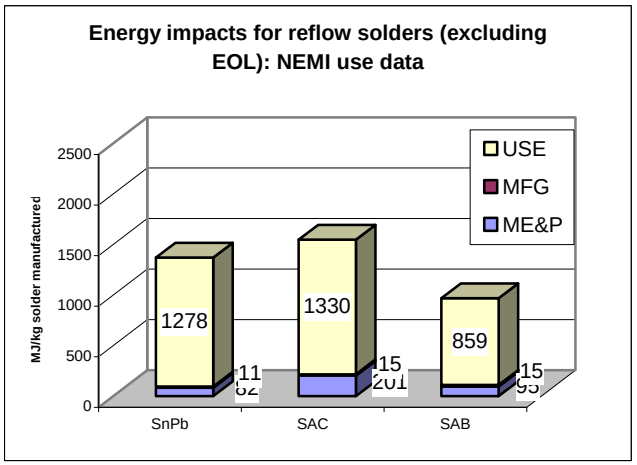


Figure 4. Life-Cycle Energy Use (excluding EOL) using NEMI Testing Data

As can be seen, while the overall values dropped considerably, the energy use during reflow still dominated the energy use category. Values ranged from a low of 86 percent for SAC to a high of 93 percent for Sn/Pb solder.

An analysis was conducted on the data to determine the sensitivity of the energy use data to variations in the mass of solder applied to the PWB. It was determined that PWB's would have to contain nearly 27 grams of SAC or over 60 grams of Sn/Pb solder per PWB assembled for the normalized energy use from reflow soldering to approach that of the other life-cycle stages. Since the mass of solder applied to a typical PWB in the consumer market ranges from 1-3 grams [3, 8], the energy consumption from the application stage appears to dominate within the range of typical assembly conditions.

Energy use has several environmental consequences, among them global warming. As an example of the importance of energy consumption within the life-cycle, the global warming impacts from energy consumption were calculated and presented here. Global warming results from a build-up of CO_2 and other greenhouse gases that are emitted to the atmosphere, some during the production of electricity and other energy sources. Global warming impacts are calculated using the mass of greenhouse gases released to the atmosphere, which are then modified using a global warming potential equivalency factor. The equivalency factor is an estimate of the chemical's atmospheric lifetime and radiative forcing referenced to a common chemical, in this case CO_2 [9].

Global warming impacts were calculated for the life-cycle energy use excluding EOL energy consumption, and presented in Figure 5. The results indicate that the energy consumed during reflow assembly of the solder is the primary influence on global warming impacts. The reflow application of solder is responsible for from 91-96 percent of the global warming impacts, depending on the solder type. While the results are preliminary and do not include the EOL processes, it is expected that this trend will hold once EOL is included in the data set, due to the enormous amount of energy required during assembly as compared to the other life-cycle stages.

DISCUSSION OF RESULTS

Energy use during the reflow process was demonstrated by this research to be a critical factor in the assessment of the overall environmental footprint of the solder product system. The test data indicate that the energy use during solder reflow assembly, once normalized for mass of solder processed, accounts for as much as 96 percent of the total energy consumed over the entire life-cycle, excluding EOL.

Energy consumption was found to vary significantly between solder alloys, primarily due to the difference in melting points and the corresponding changes in the reflow profile design parameters. Testing indicated that soldering with the SAC alloy would result in an 11 percent increase in reflow energy use and an overall increase in life-cycle energy consumption of 13.8 percent when compared to Sn/Pb. Conversely, soldering with the SAB alloy would result in a reduction in energy use of nearly 30 percent over that of Sn/Pb over the same life-cycle stages.

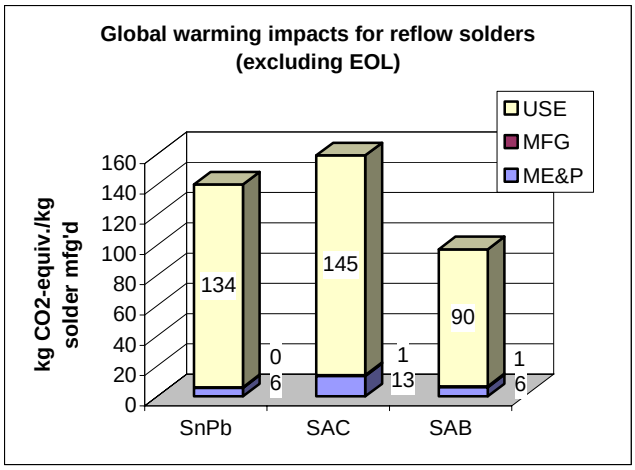


Figure 5. Global Warming Impacts from Energy use During Application

Normalizing the energy data by the mass of solder processed allows for comparison of the energy consumption across life-cycle stages, but also result in the data being sensitive to small variations in the mass of solder per board. This is problematic to the LCA study since the energy required is mostly dependent on the physical properties and flow characteristics of the alloy. There exists, at best, a tangential and fairly inconsequential correlation between the mass of solder and the total energy consumed during reflow. A sensitivity analysis was conducted to determine the potential affect of variation in the mass of solder per board processed on the calculated environmental impacts. Results of the analysis indicated that under typical electronics manufacturing scenarios the overall energy use would remain dominated by the reflow application stage.

Global warming impacts resulting from the life-cycle energy consumption (excluding EOL) were calculated and presented. As expected, the global warming impacts mirrored the relative energy use of the individual solder alloys.

Finally, the results of this study emphasize the importance of continued research into reflow techniques and equipment advances to further reduce the environmental footprint of the process. Although energy during reflow can often be achieved through process engineering techniques, such as by slowing the conveyor speed, the overall amount of energy per mass of solder may actually increase due to the reduced production of the process line.

ACKNOWEDGEMENTS

The authors would like to thank the Intel Corporation for the use of their assembly facilities during testing. The authors also would like to acknowledge the U.S. EPA Design for the Environment Program, Intel Corp., Thomson Consumer Electronics, Delphi-Delco, Agilent Technologies, Cookson Electronics, Hewlett-Packard, IBM, Pitney Bowes, and Rockwell Collins for financial support of this testing and the larger LCA effort. Finally, we would like to acknowledge the contributions of the many industry experts who consulted during the development of the testing.

REFERENCES

[1] Tiefert, K., "Roadblocks to Pb-Free Electronics: A Components Manufacturer's Perspective", JEDEC International Conference on Lead-Free Electronic Components and Assemblies Proceedings, May 1-2, 2002.

[2] Vitronics-Soltec, Phone interview of Phillip Bourgelais by Jack Geibig, University of Tennessee, November 12, 2002.

[3] Cookson Electronics, Jersey City, US: Interview with Rob Herber et al., July 2002.

[4] Parker, R, "NEMI Lead-Free Component Team Status" IPC APEX Conference Proceedings, January19-24, 2002.

[5] Flextronics International, E-mail communication from Dr. Dongkai Shangguan to Jack Geibig, University of Tennessee, March 3, 2003.

[6] Leap, G., E. Ludwig, M. Apell, "Bravo 8105 Reflow Oven power Consumption Analysis", Information from the Cookson Electronics website, August 2002. (http://www.cooksonee.com/publications/articles.htm)

[7] Deubzer, O., H. Hamano, T. Suga, H. Griese, "Lead-Free Soldering- Toxicity, Energy and Resource Consumption", IEEE Conference on Electronics and the Environment Proceedings, 2001.

[8] AIM Solder, Montreal, Canada: Interview with Karl Seelig et al., October 2002.

[9] Socolof, M.L., J.G. Overly, L.E. Kincaid, J.R. Geibig, *Desktop Computer Displays: A Life-Cycle Assessment.* EPA-744-R-01-004a, b, 2001.

APPENDIX C:
SOLDER LEACHABILITY TESTING

- Townsend, T. "Leachability of Printed Wiring Boards Containing Leaded and Lead-Free Solder." Report prepared for Abt Associates in support of the Lead-Free Solder Project, March, 2005.

Leachability of Printed Wire Boards Containing Leaded and Lead-Free Solder

Report Presented To:

Abt Associates Inc.
Project Manager: Cheryl Keenan

Report Prepared By:

Timothy G. Townsend
Associate Professor
Department of Environmental Engineering Sciences
University of Florida

May 30, 2003
(Updated March 8, 2005)

Table of Contents

1.0 Introduction

Major components of electronic devices are printed wiring boards (PWBs). Metallic solder is a major component of a printed wiring assembly (PWA), which is the PWB populated with components. The prevalent solder type used on most PWBs is a tin-lead solder. The presence of lead raises several environmental concerns, including the fate of the lead upon disposal of the discarded electronic device. Alternative solder types are available. Examples include tin-copper and tin-silver-copper. The U.S. EPA's Design for the Environment Program has worked with stakeholders to examine the life-cycle environmental impacts of tin-lead and lead-free solders. As part of this effort, a life-cycle assessment (LCA) is being conducted by the University of Tennessee. The impact and fate of the chemicals in the different solder types upon landfill disposal is an important consideration in the LCA.

To support the PWB solder LCA, laboratories at the University of Florida were contracted to conduct regulatory leaching tests on PWBs manufactured with five alternative solder types. The two leaching tests performed were the toxicity characteristic leaching procedure (TCLP) and the synthetic precipitation leaching procedure (SPLP). Both tests were developed by the U.S. Environmental Protection Agency and are often used in waste management decision making. The application and limitations of these tests are discussed. The five solder types investigated include:

- 63% Sn/ 37%Pb,
- 99.3% Sn / 0.7% Cu,
- 95.5% Sn / 4.0% Ag / 0.5% Cu,
- 96.0% Sn/ 2.5% Ag / 1.0% Bi / 0.5% Cu,
- 42.0% Sn/ 1.0% Ag / 57.0% Bi.

TCLP and SPLP tests were conducted on four different PWB sections, each with a unique configuration and solder density.

2.0 Background

2.1 The Motivation for Leaching Tests

Toxic heavy metals in process waste or discarded product have the potential to impact human health and the environment when those materials are managed improperly. The potential risk posed, however, cannot always be simply judged by the total amount of metals that are present. For some wastes, the heavy metals may be bound or encapsulated in such a fashion that they do not migrate from the waste when disposed. Leaching tests are typically used to assess the potential for heavy metals (or other chemicals) to migrate or leach from a solid waste in different disposal scenarios.

2.2 Considerations in Selecting Leaching Test Methodology

Several different leaching test methodologies have been developed by regulatory or testing agencies, or have been described in published literature. Some leaching methods are relatively simple and rapid. In these tests, wastes are exposed to a leaching solution in a laboratory container under a prescribed set of conditions and the concentrations of metals in the solution are measured after a specified time of exposure. Others evaluate the leaching of metals from wastes by constructing simulated disposal environments (such as a landfill), and observing the concentrations of the metals of concern over time.

The selection of an appropriate leaching test depends on several considerations. The objective of the leaching test is a paramount consideration. The specific use of a particular leaching test also may be required as part of a regulatory application (see the discussion of the TCLP below). For assessing the possible impact from co-disposal of a waste on landfill leachate concentrations, simple laboratory tests provide an adequate indication of how metals might leach from the waste. However, since so many factors impact metal leachability from a waste (e.g., pH, oxidation reduction potential), simple tests cannot account for all conditions that occur in a landfill. More elaborate testing protocols (e.g., lab testing under multiple testing conditions, simulated landfill experiments) may be required. Cost and time are also a major consideration in leach testing. While more elaborate testing requirements may provide more realistic results, they are more expensive and may be much more time-consuming.

Two relatively simple leaching tests are the TCLP and SPLP. The procedures are similar with the exception of the leaching fluid used. They are described in greater detail in the following sections. The rationale for selecting these tests is also discussed.

2.3 TCLP

The TCLP, EPA Method 1311, uses an acetic acid solution to simulate conditions in a municipal waste landfill where organic acids are produced as a result of waste decomposition. The TCLP requires 100 g of material for the test and the material must be size-reduced prior to leaching. Leaching takes place at a 20:1 liquid to solid ratio in a rotary extractor at 30 rpm for 18 hours. The leachates are then filtered and analyzed for the chemicals of concern.

2.4 SPLP

The SPLP, EPA Method 1312 is similar in nature to the TCLP, but utilizing a leaching fluid designed to simulate acid rainfall. It contains trace amounts of nitric and sulfuric acids. The TCLP is used to make hazardous waste determinations. The SPLP is frequently used to assess risk from environments where large amounts of organic acids are not expected to be produced (beneficial use through land application, near surface soil leachate).

2.5 Rationale for Selection of Leaching Experiments

The objective of the research was to evaluate the extent to which metals leach from PWBs assembled with different solder types. Data developed during testing would then be used to inform the LCA on potential end-of-life releases from PWBs disposed by landfilling. However, only minimal data regarding leaching of metals from PWBs with different solder types have been reported previously, the TCLP and SPLP were selected to provide a means of leaching a large number of samples over a range of conditions. The TCLP and SPLP have been found in many cases to bracket the range of leaching concentrations encountered when wastes are leached with actual landfill leachate.

3.0 Methods

3.1 Materials Tested

To assess the effects of PWB configuration on leachability, three different PWB types were selected from boards donated by industry based on their varied specifications. Solder was applied to the PWBs prior to their shipment to the University of Florida by passing the unpopulated boards through the appropriate assembly process. Unpopulated boards were used to prevent metal contamination from components and to ensure that the results reflect only the contributions from the applied solder. The PWB types selected for leachability testing are described as follows:

- A large multi-layer PWB with a variable surface circuit density (designated board type AB)
- A small PWB with a uniform high solder population density (designated as board type C)
- A small PWB with a uniform low population solder density (designated as board type D)

Solders applied to each of the PWB types to be tested included:

- 63% Sn / 37% Pb
- 57.0% Bi/ 42.0% Sn/ 1.0% Ag
- 95.5% Sn / 4.0% Ag / 0.5% Cu
- 96.0% Sn/ 2.5% Ag / 1.0% Bi / 0.5% Cu
- 99.3% Sn / 0.7% Cu

One PWB of each type was also provided with no solder applied to the surface. These unsoldered PWBs were used as sample "blanks." For boards C and D, the board types were slightly different for the Sn-Pb and Bi/Sn/Ag solder as compared to the other three solder types. The difference was minor but was observed in the weights of the populated and blank boards.

As will be discussed below, the TCLP and SPLP each require 100 g of sample. One hundred-gram sections of board type C and board type D were identified and used as samples. Two different 100-g sections of board type AB were

identified and used as samples (designated as board samples A and B). Thus a total of 4 different board samples were tested (A, B, C and D).

3.2 Sample Processing

The TCLP and SPLP require that samples be size-reduced to less than 0.95 cm. Size-reduction of the PWBs was performed using an industrial metal press. The dimensions and weights of each board were measured upon receipt. The weight data were used to estimate the board-solder density. One hundred-gram board sections were identified and these were used as the actual samples. These samples were cut into small squares to meet the size reduction requirement. To protect against contamination of the samples, the surface and blade of the metal press were washed with nitric acid before and during the cutting process.

In the case of samples C and D, the initial weight of each board type was slightly over 100 g, the size requirement for the TCLP and SPLP. Thus only a small piece on the edge of the board was identified and removed to bring the weight of the boards to approximately 100 g. The same piece was removed in each case. The remainders of the C and D boards were then size-reduced to meet the requirements of the leaching tests.

The AB boards weighed several times more than 100 g. Thus, two target areas were identified based on a visual inspection and the overall density of the boards. Board sample A was selected from a section of the board with a higher solder density than board sample B (based on visual inspection). Appendix C.2 presents a photo with the approximate location of each section of the board noted. The same area was cut from each board so that the same architecture was captured for each sample (i.e. the same amount of solder points were captured).

In both cases, because of a slight variability among the densities of each board, the final weights of each sample differed slightly. This was accounted for in the later testing by maintaining the liquid to solid ratio of 20:1 as required by the leaching tests.

3.3 Leaching Tests

The TCLP and SPLP are similar, but use different leaching fluids. The TCLP extraction solution was prepared by diluting a mixture of 11.4 mL of acetic acid (CH_3COOH) and 128.6 mL of 1N sodium hydroxide (NaOH) to two liters using reagent water. The final pH of the solution was 4.93 ± 0.05. The SPLP leaching solution was prepared by mixing 60 g of sulfuric acid with 40 g of nitric acid. The SPLP extraction fluid was prepared by adding between 0.4 and 0.5 mL of the sulfuric acid / nitric acid mixture to a 2 L volumetric flask and diluting it to volume with reagent water. The resultant pH was 4.22 +/- 0.05. The leaching tests

involved placing 100 g of reduced size PWB into a 2.2-liter extraction vessel, adding two liters of leaching solution to the vessel, tumbling for 18 ± 2 hrs, and filtering the extract using a pressurized filtration apparatus with a 0.7-μm borosilicate glass fiber filter (Environmental Express TCLP filters).

3.4 Leachate Analysis

After filtration, the extract was digested (U.S. EPA Method 3020A). The digestates were first analyzed for Pb, Ag, Cu, and Sn using a Thermo Jarrell Ash ICAP 61E Tracy Analyzer. This instrument was not, however, equipped to analyze for bismuth. Thus, the digestates were analyzed a second time using flame atomic absorption (FLAA) spectrometry using a Perkin-Elmer 5100 Atomic Absorption Spectrophotometer. While the detection limits for each element were below the RCRA toxicity characteristic concentration (TC) limit (for determining whether a solid waste is a TC hazardous waste), many of the initial results were below detection limit, even for samples where the elements were known to be a part of the solder. Thus, many of the samples were re-digested for analysis using a graphite furnace, and were reanalyzed using this more sensitive technique (the Perking Elmer 5100 Atomic Absorption Spectrophotometer). Laboratory blanks, sample spikes, field duplicates, and calibration check samples were performed as appropriate.

3.5 Estimation of Solder Density

The UF labs were asked to estimate the solder density of the various samples tested (solder density being defined as the percent of board by weight consisting of solder). The first attempt to do this was conducted by weighing each board as received, weighing the blank boards, and then subtracting the weights to determine solder weight. This method was found to be unsatisfactory for samples A and B. This resulted from the relatively small weight of solder on the boards (relative to the boards themselves) and because of inherent weight differences even between like boards. Solder density estimates for samples C and D represent the solder density over the entire PWB since the PWBs themselves weighed only slightly more than the 100 g required for the leaching tests. Even the results of the D board tests, however, were questionable because of the relatively small fraction of solder contained. Inherent differences in overall board weight could have an impact on accuracy of measurements of small solder weights.

In an effort to get a more accurate estimate of the solder densities of boards A, B, and D, sections of these boards from extra samples were digested in acid and the metal content was measured. Specifically, Bi-Sn-Ag board samples were digested and the mass of solder was estimated based on the amount of bismuth measured in the digestate. The volume of solder required to assemble a PWB is a function of both the PWB design and the geometry of the solder connections

required. Therefore, the mass of each of the solders for each PWB sample type were estimated using the ratio of the appropriate solder density (i.e. the density for the type of solder the PWB was assembled with) to the density of the Bi-Sn-Ag solder. The solder mass for each sample was then used to calculate the percentage of the overall sample weight (roughly 100 g) that was comprised of solder. These estimated densities for PWB samples undergoing leachability testing are presented in Table 1. Within each solder type (i.e. each column of the table) the board type with a higher solder density would be expected to leach more metal because of the higher concentration of metal in the given 100-g sample size consistent across PWB types. It is noted that there is no standardized digestion procedure for digesting whole boards.

Table 1. Estimated Solder Densities of PWB Samples
(units % by weight of solder on the boards)

Board Type	Sn-Pb	Sn-Ag-Bi	Sn-Ag-Cu	Sn-Ag-Bi-Cu	Sn-Cu
A	1.7%	1.8%	1.5%	1.5%	1.5%
B	0.66%	0.68%	0.58%	0.58%	0.58%
C	5.9%	6.4%	5.3%	5.6%	5.3%
D	1.0%	1.0%	0.87%	0.88%	0.87%

Notes:

- Board types A, B, and D were determined by acid digestion of a sample from the Sn-Ag-Bi board, followed by analysis of Bi.
- Board type C was determined by difference in weight between blank boards and populated boards.

4.0 Results

The results of the leaching tests are provided in Tables 2 – 5. Each table presents the duplicate results and the calculated mean for the TCLP and SPLP performed on each sample. In cases where one of the replicate measurements was below the detection limit and the other was not, the average was calculated by setting the non-detected sample concentration as the detection limit concentration. This provides a more conservative (higher) mean concentration. Values in the tables listed as 'less than' a number (e.g., <2.0) indicates the value was not detected above the detection limit.

Table 2. TCLP and SPLP Results for Sample A

Solder Type	SPLP A (mg/L)	SPLP B (mg/L)	Average SPLP (mg/L)	TCLP A (mg/L)	TCLP B (mg/L)	Average TCLP (mg/L)
63% Sn -- 37% Pb						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.76	<0.76	<0.76	<0.76	<0.76	<0.76
Cu	0.05	0.73	0.39	2.36	2.17	2.27
Pb	2.82	3.61	3.21	162	153	157
Sn	<0.02	<0.02	<0.02	<0.02	0.027	0.024
57% Bi – 42% Sn- 1% Ag						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.02	0.022	0.021	21.5	20.7	21.1
Cu	0.76	0.78	0.77	29.8	31.3	30.6
Pb	0.017	0.013	0.015	0.51	0.468	0.490
Sn	<0.02	<0.02	<0.02	0.045	<0.02	0.033
95.5% Sn – 4.0% Ag – 0.5% Cu						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.76	<0.76	<0.76	<0.76	<0.76	<0.76
Cu	1.94	1.29	1.62	29.7	28.3	29.0
Pb	<0.01	<0.01	<0.01	<0.01	0.015	0.013
Sn	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
96% Sn – 2.5% Ag –0.5% Cu – 1% Bi						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Cu	0.79	1.2	1.0	34.5	27.5	31.0
Pb	<0.01	<0.01	<0.01	<0.01	0.048	0.029
Sn	0.34	0.028	0.184	<0.02	<0.02	<0.02
99.3% Sn – 0.7% Cu						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.76	<0.76	<0.76	<0.76	<0.76	<0.76
Cu	0.94	0.73	0.84	35.7	38.4	37.0
Pb	<0.01	<0.01	<0.01	<0.01	0.026	<0.018
Sn	0.38	0.45	0.42	<0.02	<0.02	<0.02
Blank Boards						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.76	<0.76	<0.76	<0.76	<0.76	<0.76
Cu	1.01	0.81	0.91	29.2	35.8	32.5
Pb	<0.01	<0.01	<0.01	0.017	<0.01	0.014
Sn	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02

Table 3. TCLP and SPLP Results for Sample B

Solder Type	SPLP A (mg/L)	SPLP B (mg/L)	Average SPLP (mg/L)	TCLP A (mg/L)	TCLP B (mg/L)	Average TCLP (mg/L)
63% Sn -- 37% Pb						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.76	<0.76	<0.76	<0.76	<0.76	<0.76
Cu	0.07	0.06	0.065	38.9	27.7	33.3
Pb	1.78	1.59	1.68	68.1	57.7	62.9
Sn	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
57% Bi – 42% Sn- 1% Ag						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.02	<0.02	<0.02	7.54	8.99	8.27
Cu	1.03	1.01	1.02	32.8	62.1	47.5
Pb	<0.01	<0.01	<0.01	0.122	0.12	0.121
Sn	<0.02	<0.02	<0.02	0.047	<0.02	0.34
95.5% Sn – 4.0% Ag – 0.5% Cu						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.76	<0.76	<0.76	<0.76	<0.76	<0.76
Cu	1.96	1.27	1.61	49.7	50.5	50.1
Pb	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Sn	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
96% Sn – 2.5% Ag –0.5% Cu – 1% Bi						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Cu	1.31	1.36	1.34	56.3	47.0	51.7
Pb	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Sn	<0.02	0.03	0.03	<0.02	<0.02	<0.02
99.3% Sn – 0.7% Cu						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.76	<0.76	<0.76	<0.76	<0.76	<0.76
Cu	1.49	1.34	1.41	56.4	44.0	50.2
Pb	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Sn	0.068	0.033	0.051	<0.02	<0.02	<0.02
Blank Boards						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.76	<0.76	<0.76	<0.76	<0.76	<0.76
Cu	1.05	0.87	0.96	23.9	48.0	36.0
Pb	<0.01	<0.01	<0.01	0.026	<0.01	0.018
Sn	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02

Table 4. TCLP and SPLP Results for Sample C

Solder Type	SPLP A (mg/L)	SPLP B (mg/L)	Average SPLP (mg/L)	TCLP A (mg/L)	TCLP B (mg/L)	Average TCLP (mg/L)
63% Sn -- 37% Pb						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.76	<0.76	<0.76	<0.76	<0.76	<0.76
Cu	<0.02	0.11	.065	0.021	<0.02	0.021
Pb	2.33	2.66	2.50	54.5	51.4	52.9
Sn	<0.02	<0.02	<0.02	0.13	0.044	0.087
57% Bi – 42% Sn- 1% Ag						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.02	<0.02	<0.02	18.0	17.8	17.9
Cu	0.060	0.065	0.063	1.06	1.47	1.27
Pb	0.04	<0.01	0.025	0.44	0.91	0.67
Sn	<0.02	<0.02	<0.02	<0.02	.024	0.22
95.5% Sn – 4.0% Ag – 0.5% Cu						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.76	<0.76	<0.76	<0.76	<0.76	<0.76
Cu	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Pb	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Sn	<0.02	<0.02	<0.02	0.032	0.052	0.042
96% Sn – 2.5% Ag –0.5% Cu – 1% Bi						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	0.031	<0.02	0.026	<0.02	<0.02	<0.02
Cu	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Pb	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Sn	<0.02	<0.02	<0.02	<0.02	0.031	0.026
99.3% Sn – 0.7% Cu						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.76	<0.76	<0.76	<0.76	<0.76	<0.76
Cu	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Pb	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Sn	<0.02	0.036	0.028	0.14	0.088	0.114
Blank Boards						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.76	<0.76	<0.76	<0.76	<0.76	<0.76
Cu	0.068	0.054	0.061	3.13	2.07	2.60
Pb	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Sn	<0.02	0.041	0.031	<0.02	<0.02	<0.02

Table 5. TCLP and SPLP Results for Sample D

Solder Type	SPLP A (mg/L)	SPLP B (mg/L)	Average SPLP (mg/L)	TCLP A (mg/L)	TCLP B (mg/L)	Average TCLP (mg/L)
63% Sn -- 37% Pb						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.76	<0.76	<0.76	<0.76	<0.76	<0.76
Cu	0.031	0.038	0.034	0.155	0.119	0.137
Pb	2.25	2.44	2.34	18.4	16.1	17.2
Sn	<0.02	<0.02	<0.02	0.021	<0.02	0.21
57% Bi – 42% Sn- 1% Ag						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.02	<0.02	<0.02	12.3	8.21	10.3
Cu	0.503	0.021	0.262	0.444	0.361	0.387
Pb	<0.01	<0.01	<0.01	0.092	0.078	0.085
Sn	<0.02	<0.02	<0.02	0.073	<0.02	0.047
95.5% Sn – 4.0% Ag – 0.5% Cu						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.76	<0.76	<0.76	<0.76	<0.76	<0.76
Cu	<0.02	0.03	0.025	<0.02	<0.02	<0.02
Pb	0.07	<0.01	0.04	<0.01	<0.01	<0.01
Sn	<0.02	<0.02	<0.02	0.035	0.045	0.040
96% Sn – 2.5% Ag –0.5% Cu – 1% Bi						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Cu	<0.02	<0.02	<0.02	<0.02	0.039	0.03
Pb	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Sn	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
99.3% Sn – 0.7% Cu						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.76	<0.76	<0.76	<0.76	<0.76	<0.76
Cu	<0.02	<0.02	<0.02	<0.02	0.023	0.022
Pb	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Sn	<0.02	<0.02	<0.02	<0.02	0.076	0.048
Blank Boards						
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Bi	<0.76	<0.76	<0.76	<0.76	<0.76	<0.76
Cu	<0.02	<0.02	<0.02	0.478	0.657	0.568
Pb	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Sn	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02

5.0 Observations

Several observations are noted regarding the leaching results.

- Only two of the metals in the solder types are regulated as toxicity characteristic (TC) metals and thus capable of causing the boards to be RCRA hazardous wastes: Pb and Ag. The TCLP results found lead from the SnPb board to leach at concentrations greater than the RCRA TC limit (5 mg/L). Silver did not leach to concentrations greater than its TC limit (5 mg/L), and was in fact rarely encountered above the detection limit.

- The fact that silver did not leach is contradictory to some of the limited previous research regarding silver. Most of this previous research, however, was conducted on solder alone, and not as part of a PWB. It is clear, as evidenced by the silver results, and others discussed below, that the other metals present on the PWB and in solution play a large role on the relative leachability of a given metal.

- Copper was routinely measured in all of the samples. This was a result of the copper contained in the boards themselves (with no solder). The AB board leached more copper than the C and D boards. This is likely a result of the multi-layer configuration of the AB board. More of the surface was exposed for the copper to leach. Thus, the average leachate concentration from samples C and D were used to estimate copper leaching in order to minimize the effect of copper leaching from the board itself rather than the solder.

- Copper leaching was suppressed somewhat in the tin-lead solder board. This follows expected electrochemical behavior between lead and copper.

- Lead, copper and bismuth all leached greater in the TCLP relative to the SPLP. This has been observed for lead and copper in other research. The acetic acid used as part of the TCLP acts to complex with some metals and thus increases the amount that can be leached. The marked difference between TCLP and SPLP was not noted for silver and tin; both of these metals, however, were in most cases below the detection limit.

- The Bi-Sn-Ag solder appeared to contain small levels of lead, as it was observed to leach in the TCLP for all of the board types.

- The relationship between solder density (percent solder by weight on a board) and the metal leachability was examined. Only lead and bismuth provided a clear relationship of the impact of solder density. Tin and silver were not detected routinely enough to make such comparisons. Since copper came from the boards themselves, a comparison of solder density impacts could also not be made. When comparing the leachability between samples A and B and between samples C and D, both lead and bismuth showed increased concentrations for the samples with the large solder weight. This was most evident in the TCLP results (the bismuth samples were typically below detection in the SPLP samples). While earlier drafts of this document reported a mathematical equation related the solder density to the measured leachate concentrations, such equations are omitted from this version because the relationship did not hold between the A/B samples and C/D samples. It is hypothesized that the particular configuration of the A/B samples allowed more leaching of lead and bismuth to occur per mass of solder when compared to the C/D boards. Thus, even though sample C contained more solder than sample A, sample A leached more. This could be the result of different board architecture and the fact that AB was a multi-layer board. For use in the life-cycle analysis, the average of the TCLP samples from A and B were used to estimate leaching of lead, tin, silver, and bismuth. As stated earlier, copper leachability estimates used the average of TCLP samples C and D. Samples were chosen for their greater reliability for each metal type. The measured leachate concentrations were converted to mass of metal leached per unit mass of solder using the density of the solder on the board.

- Caution should be taken when applying the TCLP results too broadly. The TCLP was designed to be a rapid test for determining whether a solid waste should be a hazardous waste because of the presence of certain toxic elements. It was designed to simulate plausible worst case leaching conditions that might be encountered in a municipal solid waste (MSW) landfill. Recent research has found that lead leachability is less in typical landfill leachate relative to the TCLP (Jang, Y.; Townsend, T. *Environ. Sci. Tech.* **2003**, *37*, 4778-4784). Other metals may actually leach more in MSW leachate. Valuable future tests would include leaching different PWBs in actual landfill leachates and to construct simulated landfills for assessing leachability in more realistic environments.

Appendix C.1. Quality Assurance Results

Quality assurance results are presented in the following tables.

Table. C.1.1. Measured concentration (mg/L) of Blank QA Samples.

	Ag Conc. (mg/L)	Cu Conc. (mg/L)	Pb Conc. (mg/L)	Sn Conc. (mg/L)	Bi Conc. (mg/L)
QA Set I	<0.02	<0.02	< 0.01	<0.01	<0.76
QA Set II	<0.02	<0.02	< 0.01	<0.01	<0.76
QA Set III	<0.02	<0.02	< 0.01	<0.01	<0.76
QA Set IV	<0.02	<0.02	< 0.01	<0.01	<0.76
QA Set V	<0.02	<0.02	< 0.01	<0.01	<0.76
QA Set VI	<0.02	<0.02	< 0.01	<0.01	<0.76

Table C.1.2. QA Recovery Results for Blank Spiked Samples

	% Ag Recovery	% Cu Recovery	% Pb Recovery	% Sn Recovery	% Bi Recovery
QA Set I	94.6%	102.6%	103.6 %	108.3 %	107%
QA Set II	93%	94.6 %	101.2 %	105.7 %	115.7 %
QA Set III	106.1%	91.7 %	95.5 %	96.7 %	109.6 %
QA Set IV	114.1%	88.8 %	94%	92.4 %	110.3 %
QA Set V	96.9%	93.7%	100.2 %	94.8 %	99.7 %
QA Set VI	93.7%	94.7 %	98.2%	102.3 %	115.4%

Table C.1.3. QA Recovery Results for Blank Spiked Samples.

	% Ag Recovery	% Cu Recovery	% Pb Recovery	% Sn Recovery	% Bi Recovery*
QA Set I	96.5%	91.3%	98.4%	88.1%	104.2%
QA Set II	101.2%	91.5%	94.8%	97.9%	96.5%
QA Set III	81.2%	96.8%	98.2%	100.3%	87.2%
QA Set IV	94.2%	118.6%	96.6%	106.2%	95.5%
QA Set V	108.1%	93.6%	97.7%	106.8%	
QA Set VI	89.2%	93.7%	97.5%	103.4%	

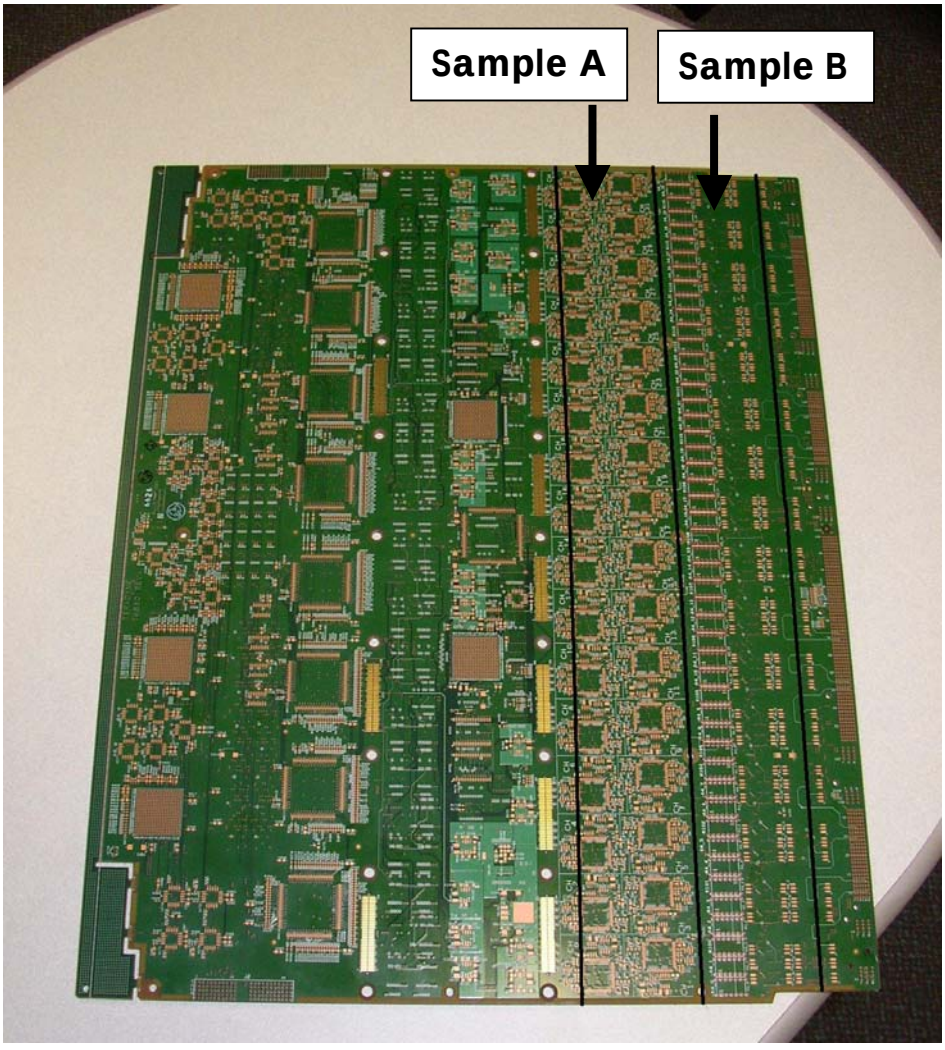
* Only four QA data points were needed for Bi analysis because of the limited sample set number analyzed.

Table C.1.4. Mean concentrations for all TCLP and SPLP Reagent Blank samples.

	Ag Conc. (mg/L)	Cu Conc. (mg/L)	Pb Conc. (mg/L)	Sn Conc. (mg/L)	Bi Conc. (mg/L)
TCLP Blanks	<0.02	<0.02	<0.01	<0.02	< 0.76
SPLP Blanks	<0.02	<0.02	<0.01	<0.02	< 0.76

Appendix C.2 Location of Sample on Board AB

Board AB consisted on one large multi-layer board. Two approximately 100-g areas were identified and cut from each board sample for leach testing. To minimize the number of cuts performed, two side-by-side locations were selected in long strips. The following figure illustrates the approximate location of these two samples, identified as A and B. The A sample visually contained a greater density of solder than the B sample.



APPENDIX D:
LIFE-CYCLE IMPACT ASSESSMENT
SUPPORT DATA (NON-TOXICITY)

Global warming potentials

Flow	Global warming potentials (100-year CO_2-equivalents)	Sources			
CF3I	<1			c	
Carbon dioxide [Inorganic emissions to air]	1	a	b	c	d
Ch2Br2	1			c	
Ch3Br	5			c	
Dichloromethane (methylene chloride) [Halogenated organic emissions to air]	10	a		c	
HFC-161 CH_3CH_2F	12	a			
CH3Cl	16			c	
Methane [Organic emissions to air (group VOC)]	23	a			
Trichloromethane (chloroform) [Halogenated organic emissions to air]	30	a			
HFC-152 CH_2FCH_2F	43	a		c	
HFC-41 Methyl fluoride 593-53-3	97	a			
HCFC 123 (dichlorotrifluoroethane) [Halogenated organic emissions to air]	120	a		c	
HFC 152a (difluoroethane) [Halogenated organic emissions to air]	120	a			
Trichloroethane [Halogenated organic emissions to air]	140	a		c	
HCFC 225ca (dichloropentafluoropropane) [Halogenated organic emissions to air]	180	a		c	
HCFC-21 CHCl2F	210			c	
Nitrous oxide (laughing gas) [Inorganic emissions to air]	296	a			
HFC 143 (trifluoroethane) [Halogenated organic emissions to air]	330	a			
ChBrF2	470			c	
HFC-32 Difluoromethane 75-10-5	550	a			
HCFC 124 (chlorotetrafluoroethane) [Halogenated organic emissions to air]	620	a		c	
HCFC 225cb (dichloropentafluoropentane) [Halogenated organic emissions to air]	620	a		c	
HFC 245ca (pentafluoropropane) [Halogenated organic emissions to air]	640	a			
HCFC 141b (dichloro-1-fluoroethane) [Halogenated organic emissions to air]	700	a		c	
HFC-365mfc $CF_3CH_2CF_2CH_3$	890	a			
HFC-245fa $CHF_2CH_2CF_3$	950	a			
HFC-134 1,1,2,2-tetrafluoro-1,2-diiodoethane 359-35-3	1100	a			
HFC-236ea CHF_2CHFCF_2	1200	a			
HFC 134a (tetrafluoroethane) [Halogenated organic emissions to air] '	1300	a			d
HFC-236cb $CH_2FCF_2CF_3$	1300	a			
Halon (1211)	1300			c	
HFC 43-10 (decafluoropentane) [Halogenated organic emissions to air]	1500	a			
CFC (soft)	1600		b		
HCFC 22 (chlorodifluoromethane) [Halogenated organic emissions to air]	1700	a			d*
Carbon tetrachloride (tetrachloromethane) [Halogenated organic emissions to air]	1800	a			
HCFC 142b (chlorodifluoroethane) [Halogenated organic emissions to air]	2400	a			
HFC 125 (pentafluoroethane) [Halogenated organic emissions to air]	3400	a	b		
HFC 227ea (heptafluoropropane) [Halogenated organic emissions to air]	3500	a			
HFC 143a (trifluoroethane) [Halogenated organic emissions to air]	4300	a			
CFC 11 (trichlorofluoromethane) [Halogenated organic emissions to air]	4600	a			
Tetrafluoromethane [Halogenated organic emissions to air]	5700	a		c	
CFC 113 (trichlorofluoroethane) [Halogenated organic emissions to air]	6000	a		c	
Halon (1301) [Halogenated organic emissions to air]	6900	a		c	

Flow	Global warming potentials (100-year CO_2-equivalents)	Sources			
CFC (hard)	7100		b		
CFC 115 (chloropentafluoroethane) [Halogenated organic emissions to air]	7200	a			
Octafluoropropane perfluoropropane 76-19-7	8600	a		c	
Decafluorobutane perfluorobutane 355-25-9	8600	a		c	
Cyclooctafluorobutane perfluorocyclobutane 115-25-3	8700				d
Dodecafluoro-pentane perfluoropentane 678-26-2	8900	a		c	
Tetradecafluorhexane perfluorohexane 355-42-0	9000	a		c	
HFC 236fa (hexafluoropropane) [Halogenated organic emissions to air]	9400	a		c	
CFC 114 (dichlorotetrafluoroethane) [Halogenated organic emissions to air]	9800	a		c	
CFC 12 (dichlorodifluoromethane) [Halogenated organic emissions to air]	10600	a		c	
CFC 116 (hexafluoroethane) [Halogenated organic emissions to air]	11900	a			
HFC 23 (trifluoromethane) [Halogenated organic emissions to air]	12000	a			
CFC 13 (chlorotrifluoromethane) [Halogenated organic emissions to air]	14000	a		c	
Sulphur hexafluoride [Inorganic emissions to air]	22200	a		c	

Sources:
(a) IPPC 2001 Report: IPCC - Albritton, D.L. ; Meiro Filho, L.G.. www.ipcc.ch/pub/wg1TARtechsum.pdf.
(b) Eco-Indicator 1995.
(c) WMO 98 report: The Scientific Assessment of Ozone Depletion,1998. World Meteorological Organisation, Global Ozone Research and Monitoring Project. Report No. 44. 100 year.
(d) LCA Handbook: Houghton et al., 1994 & 1996; GWP values for the substances marked with * are 1994.

Ozone depletion potentials

Flow	Ozone depletion potential (ODP) (CFC-11 equivalents)	Sources					
HCFC- 151 C2H4FCl	0.005	a*					
HCFC-251 C3H4FCl3	0.01	a*					
HCFC-123	0.02	a' *		c			
Methyl Chloride	0.02		b		d		
HCFC-31 CH2FCL	0.02	a*					
HCFC-261 C3H5FCl2	0.02	a*					
HCFC-262 C3H5F2Cl	0.02	a*					
HCFC-124	0.022	a' *		c			
HCFC-225ca	0.025	a' *		c			
HCFC-253 C3H4F3Cl	0.03	a*					
HCFC-271 C3H6FCl	0.03	a*					
HCFC-225cb	0.033	a' *		c			
HCFC-21 CHFCl2	0.04	a' *					
HCFC-121 C2HFCl4	0.04	a*					
HCFC-252 C3H4F2Cl2	0.04	a*					
HCFC-131 C2H2FCl3	0.05	a*					
HCFC-132 C2H2F2Cl2	0.05	a*					
HCFC 22 (chlorodifluoromethane)	0.055	a*		c			
CFC (soft)	0.055			c			
HCFC-133 C2H2F3Cl	0.06	a*					
HCFC 142b (chlorodifluoroethane)	0.065	a*		c		e	
HCFC-141 C2H3FCl2	0.07	a*					
HCFC-142 C2H3F2Cl	0.07	a*					
HCFC - 221 C3HFCl6	0.07	a*					
HCFC-225 C3HF5Cl2	0.07	a*					
HCFC-122 C2HF2Cl3	0.08	a*					
HCFC-223 C3HF3Cl4	0.08	a*					
HCFC-222 C3HF2Cl5	0.09	a*					
HCFC-224 C3HF4Cl3	0.09	a*					
HCFC-231 C3H2FCl5	0.09	a*					
HCFC-241 C3H3FCl3	0.09	a*					
Trichloroethane [Halogenated organic emissions to air]	0.1	a**					
HCFC-226 C3HF6Cl	0.1	a*					
HCFC-232 C3H2F2Cl4	0.1	a*					
C2H4FBr	0.1	a*					
HCFC 141b (dichloro-1-fluoroethane) [Halogenated organic emissions to air]	0.11	a*		c			
HCFC-243 C3H3F3Cl2	0.12	a*					
HCFC-242 C3H3F2Cl3	0.13	a*					
Halon-2311	0.14			c	d		
HBFC-2311	0.14		b*				
HCFC-244 C3H3F4Cl	0.14	a*					
HCFC-233 C3H2F3Cl3	0.23	a*					
Halon-2401	0.25			c	d		
HBFC-2401	0.25						
HCFC- 234 C3H2F4Cl2	0.28	a*					

Flow	Ozone depletion potential (ODP) (CFC-11 equivalents)	Sources					
C3H4FBr3	0.3	a*					
C3H5FBr2	0.4	a					
HCFC-235 C3H2F5Cl	0.52	a*					
air]	0.6	a"				e	
Methyl bromide [Halogenated organic emissions to air]	0.6	a		c			
C3H6FBr	0.7	a*					
CH2FBr	0.73	a*					
CHF2Br HBFC-22B1; bromodifluoromethane	0.74	a"					
CFC 113 (trichlorofluoroethane) [Halogenated organic emissions to air]	0.8	a"				e	
C2HFBr4	0.8	a*					
C3H4F3Br	0.8	a*					
C3H5F2Br	0.8	a*					
CFC 114 (dichlorotetrafluoroethane) [Halogenated organic emissions to	1	a"				e	
CFC 13 (chlorotrifluoromethane) [Halogenated organic emissions to air]	1	a				e	
CFC 12 (dichlorodifluoromethane) [Halogenated organic emissions to air]	1	a"		c		e	
CFC 11 (trichlorofluoromethane) [Halogenated organic emissions to air]	1	a"	b	c	d	e	f
CFC-111 pentachlorofluoroethane	1	a					
CFC- 112 Tetrachlorodifluoroethane	1	a					
CFC-211 heptachlorofluoropropane	1	a					
CFC-212 hexachlorotrifluoropropane	1	a					
CFC-213 pentachlorotrifluoropropane	1	a					
CFC-214 Tetrachlorotetrafluoropropane	1	a					
CFC-215 trichloropentafluoropropane	1	a					
CFC-216 dichlorohexafluoropropane	1	a					
CFC-217 monochloroheptafluoropropane	1	a					
CFC (hard)	1			c			
CHFBr2	1	a*					
C3H4F2Br2	1	a*					
Carbon tetrachloride (tetrachloromethane) [Halogenated organic emissions to air]	1.1	a				e	
C2H2FBr3	1.1	a*					
C2H3F2Br	1.1	a*					
C2HF4Br	1.2	a*					
Halon- 1202	1.25		b*	c	d		
Halon-1201	1.4			c	d		
HBFC-1201	1.4		b*				
C2H2F2Br2	1.5	a*					
C3HFBr6	1.5	a*					
C2HF3Br2	1.6	a*					
C2H2F3Br	1.6	a*					
C2H3FBr2	1.7	a*					
C2HF2Br3	1.8	a*					
C3HF3Br4	1.8	a*					
C3HF2Br5	1.9	a*					
C3H2FBr5	1.9	a*					
C3H3FBr4	1.9	a*					

Flow	Ozone depletion potential (ODP) (CFC-11 equivalents)	Sources					
C3HF5Br2	2	a*					
C3H2F2Br4	2.1	a*					
C3HF4Br3	2.2	a*					
C3H3F3Br2	2.5	a*					
Halon (1211) [Halogenated organic emissions to air]	3	a''				e	
C3H3F2Br3	3.1	a*					
C3HF6Br	3.3	a*					
C3H3F4Br	4.4	a*					
C3H2F3Br3	5.6	a*					
Halon (2404) [Halogenated organic emissions to air]	6					e	
Halon 2402 dibromotetrafluoroethane 124-73-2	6	a*					
C3H2F4Br2	7.5	a*					
Halon (1301) [Halogenated organic emissions to air]	10	a''				e	
C3H2F5Br	14	a*					

Sources:

(a) Montreal Protocol / UNEP (www.uneptie.org/ozonaction/compliance/protocol/ods.html).

a'' These values are estimates and will be revised periodically.

a** This formula does not refer to 1,1,2-trichloroethane.

a' Identifies the most commercially viable substances with ODP values listed against them to be used for the purposes of the Protocol.

a* Where a range of ODPs is indicated, the highest value in that range shall be used for the purposes of the Protocol.

(b) WMO (World Meteorological Organisation), 1999. *Scientific Assessment of Ozone Depletion: 1998.* Global Ozone Research and Monitoring project - Report no. 44. Geneva. in Guinee, 2002: LCA Handbook, Institute of Environmental Sciences, The Netherlands.

b* WMO (World Meteorological Organisation), 1992. Scientific Assessment of Ozone Depletion: 1991. Global Ozone Research and Monitoring Project - Report no. 25. Geneva. in Guinee, 2002: LCA Handbook, Institute of Environmental Sciences, The Netherlands.

Solomon, S. and Wuebbles, D.J. (1995) Ozone Depletion Potentials, Global Warming Potentials and Future Chlorine/Bromine Loading, in Scientific Assessment of Ozone Depletion: 1994 (Assessment Co-Chairs D.L. Albritton, R.T. Watson and P.J. Aucamp), World Meteorological Organisation, Global Ozone Research and Monitoring Project, Report No. 37, World Meteorological Organisation, Geneva.

(c) Heijungs et al. (1992) and The Eco-Indicator -Final Report. NOH. 1995.

(d) Hauschild 1998 and Eco-Indicator 1999.

(e) The Scientific Assessment of Ozone Depletion,1998. World Meteorological Organisation, Global Ozone Research and Monitoring Project. Report No. 44. In GaBi3 (GaBi, 2000).

(f) Solomon, S. and Albritton, D.L. (1992) Time-Dependent Ozone Depletion Potentials for Short and Long-Term Forecasts. *Nature,* **357,** 33-37. In Wenzel and Hauschild, 1995.

Photochemical oxidant potential

Flow	Photochemical oxidant potential	Sources					
Chloromethane (methyl chloride) [Halogenated organic emissions to air]	0.005	a					
Methane [Organic emissions to air (group VOC)] *(alkane)*	0.006	a	b				
Trichloroethane [Halogenated organic emissions to air] (Methyl chloroform)	0.021			c			
Carbon tetrachloride (tetrachloromethane) [Halogenated organic emissions to air]	0.021			c			
Polychlorinated dibenzo-p-dioxins (2,3,7,8 - TCDD) [Halogenated organic emissions to air]	0.021						f
Polychlorinated dibenzo-p-furans (2,3,7,8 - TCDD) [Halogenated organic emissions to air]	0.021						f
Dichloroethane (isomers) [Group NMVOC to air]	0.021			c			f
Tetrafluoromethane [Halogenated organic emissions to air]	0.021						f
air]	0.021						f
Dichlorobenzene (p-DCB; 1,4-dichlorobenzene) [Halogenated organic emissions to air]	0.021						f
Chlorobenzene [Halogenated organic emissions to air]	0.021						f
CFC 113 (trichlorofluoroethane) [Halogenated organic emissions to air]	0.021						f
Vinyl chloride (VCM; chloroethene) [Halogenated organic emissions to air]	0.021			c			f
air]	0.021						f
Polychlorinated biphenyls (PCB unspecified) [Halogenated organic emissions to air]	0.021						f
CFC 22 (chlorodifluoromethane) [Halogenated organic emissions to air]	0.021						f
air]	0.021						f
CFC 142b (chlorodifluoroethane) [Halogenated organic emissions to air]	0.021						f
CFC 134a (tetrafluoroethane) [Halogenated organic emissions to air]	0.021						f
CFC 13 (chlorotrifluoromethane) [Halogenated organic emissions to air]	0.021						f
CFC 125 (pentafluoroethane) [Halogenated organic emissions to air]	0.021						f
CFC 12 (dichlorodifluoromethane) [Halogenated organic emissions to air]	0.021						f
Dichlorobenzene (o-DCB; 1,2-dichlorobenzene) [Halogenated organic emissions to air]	0.021						f
CFC 116 (hexafluoroethane) [Halogenated organic emissions to air]	0.021						f
air]	0.021						f
CFC 11 (trichlorofluoromethane) [Halogenated organic emissions to air]	0.021						f
CxHy Chloro	0.021			c			
Trichloromethane (chloroform) [Halogenated organic emissions to air]	0.023	a					
dimethyl carbonate	0.025	a*					
Methyl Formate	0.027	a*					
Nitrogen Dioxide	0.028	a**					
Tetrachloroethene (perchloroethylene) [Halogenated organic emissions to air] (tetrachloroethylene)	0.029	a					
Formic acid	0.032	a					
Carbon monoxide [Inorganic emissions to air]	0.036						f
Sulphur Dioxide	0.048	a*					
Tertiary - Butyl Acetate	0.053	a*					
Methyl acetate [Group NMVOC to air] (esters)	0.059	a*					

Flow	Photochemical oxidant potential	Sources					
Dichloromethane (methylene chloride) [Halogenated organic emissions to air]	0.068	a					
Ethene (acetylene) [Group NMVOC to air] *(alkyne)*	0.085		b				
Tertiary Butanol	0.106	a*					
Ethane [Group NMVOC to air] *(alkane)*	0.123	a	b	c			
Methanol [Group NMVOC to air] *(alcohol)*	0.14	a*					
Styrene [Group NMVOC to air]	0.142	a					
2-methyl 2-butanol	0.142		b				
Propionic acid (79-09-4)	0.15	a					
Dimethoxy methane (Methylal)	0.164	a*					
Neopentane (dimethylpropane)	0.173	a	b				
Methyl tert-Butyl Ether	0.175	a*					
Propane [Group NMVOC to air]*(alkanes)*	0.176	a	b				
Acetone (dimethylcetone) [Group NMVOC to air] (*ketone)*	0.178			c			f
Propanol (iso-propanol; isopropanol) [Group NMVOC to air]	0.188	a*					
Benzene [Group NMVOC to air] (*Aromatic)*	0.189			c			f
Dimethyl Ether	0.189	a*					
Furfuryl alcohol [Group NMVOC to air]	0.196						f
Butylene glycol (butane diol) [Group NMVOC to air]	0.196						f
Alcohols	0.196			c			
Methyl Ether Acetate	0.2				d		
Ethylene acetate (ethyl acetate) [Group NMVOC to air]	0.209	a*					
Isopropyl acetate *(Esters)*	0.211	a*					
Propyl acetate [Group NMVOC to air]	0.215						f
Vinyl acetate	0.223			c			
2,2- dimethylbutane *(alkanes)*	0.241		b				
Ethyl- trans-Butyl Ether	0.244	a*					
sec-Butyl Acetate	0.275	a*					
Cyclohexanone [Group NMVOC to air]	0.299	a	b				
Butan-2-diol (look at item 44)	0.3				d	e	
Isobutane CH(CH3)3 *(alkanes)*	0.307	a	b				
Diacetone alcohol	0.307	a*					
Butylacetate [Group NMVOC to air]	0.323						f
Methyl tert-butylketone (Pinacolin)	0.323	a	b				
Trichloroethene (isomers) [Halogenated organic emissions to air] (trichloroethylene)	0.325	a					
Ketones	0.326			c			
VOC (unspecified) [Organic emissions to air (group VOC)]	0.337						f
n-dodecane *(alkanes)*	0.357	a	b				
Isobutanol (*alcohol)*	0.36	a*					
3-methylhexane *(alkanes)*	0.364		b				
Methyl Isopropyl Ketone	0.364	a	b				
3-methyl 2-butanol	0.366		b				
Ethylene glycol	0.373	a*					
Methyl ethyl ketone	0.373		b				
Terpentine	0.377			c			
Ethylene Oxide	0.377			c			
Hydroxy compounds *Item 67*	0.377			c			

Flow	Photochemical oxidant potential	Sources					
Methyl mercaptan	0.377			c			
Ethane diol	0.382		b				
n-decane *(alkanes)*	0.384		b				
n-undecane *(alkanes)*	0.384		b				
Decane	0.384	a					
Dichloroethene (trans)	0.392	a					
Pentane (n-pentane) [Group NMVOC to air] (*alkanes)*	0.395	a	b				
Crude Oil	0.398			c			
CxHy Hydrocarbons	0.398			c			
Petrol	0.398			c			
Diisopropyl ether	0.398	a*					
Ethanol (ethyl alcohol) [Group NMVOC to air] *(alcohol)*	0.399	a*					
2-methylnonane *(alkanes)*	0.4				d	e	
Butanol *(alcohol)*	0.4					e	
Isobutyl Acetate	0.4				d		
isopentane CH2CH(CH3)C2H5 *(alkanes)*	0.405	a	b				
2-methyl 1-butanol	0.407		b				
Butane (n-butane) [Group NMVOC to air]*(alkanes)*	0.41						f
2-methylhexane *(alkanes)*	0.411		b				
3-methyl 1-butanol	0.412		b				
n-nonane *(alkanes)*	0.414	a	b				
Diethyl Ketone	0.414	a					
3-pentanone	0.414		b				
NMVOC (unspecified) [Group NMVOC to air]	0.416			c			f
2-methylpentane *(alkanes)*	0.42		b				
3-pentanol	0.422		b				
Nitrogen mono oxide	0.427	a					
Aldehydes	0.443			c			
Diethyl Ether	0.445	a*					
sec-Butanol	0.447	a*					
Octane	0.453	a					
Propylene glycol [Group NMVOC to air]	0.457	a*					
Propane diol	0.457		b				
3-methylpentane *(alkanes)*	0.479		b				
Hexane (isomers) [Group NMVOC to air] (alkanes)	0.482	a	b				
Methyl Isobutyl ketone (hexone) (*ketone)*	0.49	a	b				
Octane [Group NMVOC to air] *(alkanes)*	0.493						f
Heptane (isomers) [Group NMVOC to air] *(alkane)*	0.494	a	b				
2-methylheptane *(alkanes)*	0.5				d	e	
2-methyloctane *(alkanes)*	0.5				d	e	
Isopropylbenzene *(aromatic)*	0.5		b		d		
Methyl ether	0.5				d	e	
Isopropyl benzene (cumene)	0.5	a					
Isobutyraldehyde (iso-butanal) separate in Source a	0.514	a	b				
Cyclohexanol [Group NMVOC to air]	0.518	a*					
Formaldehyde (methanal) [Group NMVOC to air] *(aldehydes)*	0.519	a	b				
Ethanal (Acetaldehyde) [Group NMVOC to air]	0.52701						f
2,3- dimethylbutane *(alkanes)*	0.541		b				

Flow	Photochemical oxidant potential	Sources					
n-Propanol	0.543		b				
2-pentanone	0.548		b				
Methyl propyl Ketone	0.548	a					
Butyraldehyde (n-; iso-butanal) [Group NMVOC to air]	0.568						f
Hexa-2-one	0.572	a	b				
Hexa-3-one	0.599	a	b				
Methylcyclohexane *(alkanes)*	0.6					e	
n-butanol	0.612		b				
Isobutene *(alkene) isobutylene*	0.627	a					
Methyl propene	0.627		b				
n-propylbenzene *(aromatic)*	0.636		b				
Toluene (methyl benzene) [Group NMVOC to air] *(aromatic)*	0.637	a	b				
Acetaldehyde (*aldehyde)*	0.641		b				
3-methylbut-1-ene (*alkene)*	0.671		b				
Allyl chloride	0.7					e	
Ethyl benzene [Group NMVOC to air] *(aromatic)*	0.73	a	b				
Polycyclic aromatic hydrocarbons (PAH) [Group PAH to air]	0.76098						f
Benzo{a}pyrene [Group PAH to air]	0.761						f
Cyclohexane (hexahydro benzene) [Group NMVOC to air]	0.761						f
Phenol (hydroxy benzene) [Group NMVOC to air]	0.761			c			f
Cyclopentanone [Group NMVOC to air]	0.761						f
Caprolactam	0.761			c			
Chlorophenols	0.761			c			
CxHy Aromatic	0.761			c			
Diphenyl	0.761			c			
Hexachlorobiphenyl	0.761			c			
Naphthalene	0.761			c			
Phthalic acid anhydride	0.761			c			
Valeraldehyde (*aldehyde) (p*entanaldehyde)	0.765	a					
Pentanal	0.765		b				
2-methylbut-1-ene *(alkene)*	0.771		b				
Xylene (dimethyl benzene) [Group NMVOC to air]	0.777						f
Propionaldehyde Propanol (aldehyde)	0.798	a	b				
Acrolein *(aldehyde)*	0.8				d	e	
2-methylbut-2-ene (*alkene)*	0.842		b				
1,3 - butadiene (look at 74)	0.851		b				
1-hexene	0.874		b				
o-ethyltoluene *(aromatic)* (2-ethyltoluene)	0.898	a	b				
Butadiene [Group NMVOC to air]	0.906						f
p-ethyltoluene *(aromatic)* (4-ethyltoluene)	0.906	a	b				
Butene (vinyl acetylene) [Group NMVOC to air]	0.959						f
1-pentene *(alkene)*	0.977		b				
Ethene (ethylene) [Group NMVOC to air]*(alkenes)*	1	a	b	c	d	e	f
p-xylene (*aromatic)*	1.01	a	b				
m-ethyltoluene *(aromatic)* (3-ethyltoluene)	1.02	a	b				
o-xylene (*Aromatic)*	1.05	a	b				
Trans-2-hexene	1.07	a	b				
cis 2-hexene	1.07		b				

Flow	Photochemical oxidant potential	Sources					
1-butene *(alkene)*	1.08		b				
Isoprene *(alkene)*	1.09	a	b				
1,2,5-trimethylbenzene *(aromatic)*	1.1					e	
m-xylene (*aromatic)*	1.11	a	b				
Propene (propylene) [Group NMVOC to air]*(alkene)*	1.12	a	b				
2-pentene (trans) *(alkene)*	1.12	a	b				
cis 2-penene	1.12		b				
2-butene (trans) *(alkene)*	1.13	a	b				
cis 2-butene	1.15		b				
1,2,3- Trimethylbenzene *(aromatic)*	1.27		b				
1,2,4- trimethylbenzene *(aromatic)*	1.28		b				
3,5 dimethyl toluene	1.3		b				
3,5 dimethyl ethyl benzene	1.32		b				
1,3,5 - trimethyl benzene	1.38		b				

Sources:

(a) LCA Handbook: Derwent, R.G., M.E. Jenkin, S.M. Saunders & M.J. Piling, 1998. *Photochemical Ozone Creation Potentials for Organic Compounds in Northwest Europe Calculated with a Master Chemical Mechanism. Atmos. Environ. 32 (14-15): 2429-2441.*

* updated from Jenkin, M.E. & G.D. Hayman, 1999. *Photochemical Ozone Creation Potentials for Oxygenated Volatile Organic Compounds: Sensitivity to Variations in Kinetic and Mechanistic Parameters.*

** value for inorganic substances from Derwent, R.G., M.E. Jenkin & S.M. Saunders, 1996. *Photochemical Ozone Creation Potentials for a Large Number of Reactive Hydrocarbons under European Conditions. Atmos.*

(b) Eco-Indicator 1999.

(c) Eco-Indicator 1995. j ( )

Photochemical Ozone Creation Potentials: A Study of Different Concepts. J. Air Waste Manage. Assoc. 42(9), 1152-1158.

(e) High NO x: Wenzel and Hauschild: Anderson- Skold, Y., Grennfelt, P. and Pleijel, K. (1992) Photochemical Ozone Creation Potentials: A Study of Different Concepts. J. Air Waste Manage. Assoc. 42(9),

(f) GaBi3 (PE & IKP, 2000).

Acidification potentials

Flow	Acidification potential (SO_2-equivalents)	Sources			
Tetrachloroethene (perchloroethylene) [Halogenated organic emissions to air]	0.19		b		
Hydrogen bromine (hydrobromic acid) [Inorganic emissions to air]	0.396		b		
Nitric acid [Inorganic emissions to air]	0.508		b		
Chloromethane (methyl chloride) [Halogenated organic emissions to air]	0.634		b		
Vinyl chloride (VCM; chloroethene) [Halogenated organic emissions to air]	0.634		b		
Sulphuric acid [Inorganic emissions to air]	0.653		b		
Nitrogen Dioxides	0.7	a		c	d
Nitrogen oxides [Inorganic emissions to air] (NOx)	0.7	a	b	c	d
Trichloroethane [Halogenated organic emissions to air]	0.72		b		
Trichloroethene (isomers) [Halogenated organic emissions to air]	0.72		b		
Dichloromethane (methylene chloride) [Halogenated organic emissions to air]	0.744		b		
Sulfur Trioxide	0.8	a		c	
Trichloromethane (chloroform) [Halogenated organic emissions to air]	0.803		b		
Carbon tetrachloride (tetrachloromethane) [Halogenated organic emissions to air	0.83		b		
Hydrochloric Acid	0.88			c	d
Hydrogen chloride [Inorganic emissions to air]	0.88	a	b		
Phosphoric Acid	0.98	a		c	
Sulfur Oxides	1				d
Sulphur dioxide [Inorganic emissions to air]	1	a	b	c	d
Nitric Oxide	1.07			c	d
Nitrogen monoxide	1.07	a			
Hydrogen cyanide (prussic acid) [Inorganic emissions to air]	1.185		b		
Hydrofluoric acid	1.6			c	d
Hydrogen fluoride [Inorganic emissions to air]	1.6	a	b		
Ammonia [Inorganic emissions to air]	1.88	a	b	c	d
Hydrogen sulphide [Inorganic emissions to air]	1.88		b	c	

Sources:

(a) LCA Handbook: Heijungs, R., J.B. Guinee, G. Huppes, R.M. Lankreijer, H.A. Udo de Haes, A. Wegener Sleeswijk, A.M.M. Ansems, P.G. Eggels, R. van Duin, and H.P. de Goede. 1992. Environmental Life-Cycle Assesment of Products. Vol. I: Guide, and Vol II: Backgrounds. Leiden: CML Center for Environmental Studies, Leiden University.

(b) GaBi3 (PE & IKP, 2000).

(c) Hauschild and Wenzel - Hauschilld, M.Z. and Wenzel, H. Acidification as Assessment Criterion in the Environmental Assessment of Products, in: *Scientific Background for Environmental Assessment of Products* (eds M. Hauschild and H. Wenzel), Chapman & Hall, London. 1997.

(d) Eco-Indicator 1995.

Eutrophication potentials of material flows to water

Flow	Eutrophication potential (phosphate-equivalents)	Sources	
Chemical oxygen demand (COD) [Analytical measures to water]	0.022	a	b
Nitrate [Inorganic emissions to water]	0.1	a	b
Nitric Acid	0.1	a	
Nitrogen dioxide	0.13	a	
Nitrogen Monoxide	0.2	a	
Ammonium [Inorganic emissions to water]	0.33	a	b
Ammonia [Inorganic emissions to water]	0.35	a	
Total Nitrogen	0.42	a	
Phosphoric acid	0.97	a	
Phosphate [Inorganic emissions to water]	1	a	b
Phosphorous oxide	1.34	a	
Total Phosphorus	3.06	a	

Sources:
(a) LCA Handbook (2001): Based on Heijungs et al. (1992) with some modifications.
(b) GaBi3 (PE & IKP 2000).

APPENDIX E:
LIFE-CYCLE IMPACT ASSESSMENT
SUPPORT DATA (TOXICITY)

APPENDIX E:

SUPPORTING TOXICITY DATA

E.1 TOXICITY DATA COLLECTION

Background:

In the Lead Free Solder Project (LFSP), human and ecological toxicity impacts are calculated by using a chemical ranking method (described in Chapter 3, Sections 3.2.11 through 3.2.13). This method was originally developed for a life-cycle assessment (LCA) done with support from the EPA Office of Research and Development (ORD) and Saturn Corporation. It was updated for the EPA's Design for the Environment (DfE) Program Computer Display Project (CDP) in consultation with ORD. The final CDP method was reviewed by ORD as well as EPA's Office of Pollution Prevention and Toxics Risk Assessment Division (RAD) prior to publication (Socolof et al., 2001). Other minor updates have been made for this LFSP, which include (1) separating chronic heath impacts into cancer impacts and chronic non-cancer impacts (for both public and occupational impacts) and (2) removing the presentation of the terrestrial ecotoxicity impact category.

Separating the chronic human impacts into two separate categories was done because the hazard values (HVs) calculated for each of these two impact categories are calculated based on geometric means for different endpoints. For cancer impacts, the HV is based on the geometric mean of cancer slope factors. The geometric mean for cancer slope factors are largely influenced by the slope factors for dioxins, which are very high. Thus the associated hazard values of most cancer impacts have numerically small HVs (since the HV is calculated by dividing the chemical-specific slope factor by the geometric mean). Compared to the non-cancer HVs, the cancer HVs are generally much smaller numbers. Therefore, combining the two impact scores into one impact category causes the non-cancer impacts to overshadow the cancer impacts. Therefore, to observe any real resolution in the cancer impact category, the cancer and non-cancer impact categories have been separated for the LFSP.

The other change from the CDP was to remove the terrestrial toxicity impact category as being presented independently, because the chronic non-cancer impacts presented alone are calculated the same way as the terrestrial ecotoxicity impacts. Thus, the terrestrial ecotoxicity impacts are represented by the non-cancer impacts and thus are not presented separately in the LFSP.

In the LCA, there is no intent to conduct a full risk assessment or even a screening level risk assessment, given that there are no real spatial or temporal boundaries to this global, industry-wide LCA. In order to provide some weighting of the inventory data to represent potential toxicity, basic toxicity data (e.g., a no observable adverse effect level [NOAEL] for chronic, non-carcinogenic effects) are used. The intent is to modify the inventory data by the inherent toxicity of the material to provide a relative toxicity measure.

Table E-1 lists the toxicity data used for potentially toxic chemicals in the LFSP

inventory, and Table E-2 lists the associated HVs calculated per the methodologies described in Section 3.2.11 through 3.2.13. To save project resources, toxicity data that had been collected for previous DfE projects were used in the LFSP. Toxicity data used prior to this project were collected by Syracuse Research Corporation (SRC) (under contract with EPA) and EPA's RAD. Chemicals identified in the LFSP inventory, for which toxicity data had not been previously collected, were collected by the Toxicity and Hazard Assessment Group in the Life Sciences Division at the Oak Ridge National Laboratory (ORNL). ORNL conducted their search in April, 2003, and the data were subsequently reviewed and/or supplemented by EPA's RAD. The description below presents the method used to collect the LFSP toxicity data.

Data Collection Approach:

Once inventory data are collected for the project, the inventory flows are checked to determine if they are potentially toxic. The lists of potentially toxic and non-toxic chemicals were reviewed by EPA. Those excluded from the toxicity list, and assumed to be non-toxic are provided in Table E-3. The chemicals then deemed potentially toxic are assembled for toxicity data collection. The data are first checked for correct chemical name and Chemical Abstracts Service (CAS) registry number, and the associated inventory disposition (e.g., release to water) is identified to help determine classification into different toxicity impact categories. Classification helps determine what toxicity data need to be collected. For example, if an inventory flow is released to water, it will require aquatic toxicity data.

For most of the chemicals identified in the inventory of the life-cycle of the solder alternatives being evaluated, toxicity data were collected for the CDP. For these chemicals, data from the CDP were used. For new chemicals identified in this LCA, chronic human toxicity endpoints and both acute and chronic aquatic toxicity endpoints were searched. The following specific endpoints are used for calculating human toxicity scores:

- inhalation or oral NOAEL (or inhalation or oral LOAEL),
- cancer slope factors, and
- cancer weight of evidence (WOE).

For ecological toxicity, the following endpoints are used for calculating aquatic toxicity:

- fish LC50, and
- fish NOEL.

In some cases, all endpoints needed to be searched, and in others, only aquatic toxicity endpoints need to be searched. This simply depended on what data were already available from the previous studies.

EPA's RAD provided guidance for collecting toxicity data for DfE Cleaner Technologies Substitutes Assessments. This served as the basis for data collection for this LCA; however, it was modified as applicable to an LCA. As stated in the RAD guidance, when searching for the toxicity endpoints, the first sources to be reviewed were to be:

- EPA's Integrated Risk Information System (IRIS) (http://www.epa.gov/iris/),
- Agency for Toxic Substances and Disease Registry (ATSDR) toxicological profiles,
- EPA's High Production Volume (HPV) Challenge robust summaries and supporting documents, and
- Organization for Economic Cooperation and Development's (OECD's) Screening Information Data Set (SIDS) robust summaries and supporting documents.

If endpoints from these sources were found, and did not conflict with other sources from this list, those data were chosen. Applicable data were included in a matrix of the chemicals and endpoints of interest and provided to UT by ORNL. If more than one value was found for an endpoint, decisions of what data to use were discussed between ORNL and UT and then UT and EPA.

If endpoints were not found from the above sources, the following databases were to be searched:

- Toxline,
- Medline (as appropriate, depending on the toxicity endpoint or endpoints for which data are being sought), and
- TSCATS (Toxic Substances Control Act Test Submissions)–the EPA database that holds data submitted to the Agency under TSCA sections 4 and 8). Although data in TSCATS may be unpublished and, therefore, not subjected to peer review by the editors of a journal, the data may provide useful information on particular chemicals and can be considered for preparation of robust summaries if the TSCATS data meet Agency standards for data quality/data adequacy.

For studies providing endpoint data found in these or other alternative sources, ORNL was instructed to prepare brief summaries of the studies (following the format of a robust summary to the extent possible, see www.epa.gov/chemrtk/robusumgd.htm). ORNL would then document which value was chosen and explain why. Consideration of EPA's criteria for data quality/data adequacy would also be incorporated into the explanation (www.epa.gov/opptintr/chemrtk/datadfin.htm).

Toxicity Data:

Table E-4 presents the final chosen toxicity data and, where necessary, provides comments on the selection process. Tables E-5, E-6, and E-7 provide the supporting toxicity data collected for the LFSP project by ORNL. The data in Tables E-5, E-6, and E-7 were reviewed by UT. The chosen data were then reviewed by EPA and the actual data points used in the LFSP life-cycle impact assessment (LCIA) are also provided in Table E-4.

The LCIA methodology is similar to that which was used for the CDP, and is described in Section 3.1 of this report. The toxicity data required for the LCIA, and what was requested from ORNL, are as follows:

- Cancer (mammalian toxicity)
  - oral SF
  - inhalation SF
  - WOE
- Non-cancer (mammalian toxicity)
  - oral NOAEL (or LOAEL)
  - inhalation NOAEL (or LOAEL)
- Aquatic ecotoxicity
  - LC50
  - NOEL

In the cases where chronic ecotoxicity (e.g., no observable effect level [NOEL]) data are not available, the log K_{ow} and the LC_{50} are used to predict the NOEL (described in Section 3.1.2.13). The log K_{ow} values were determined using the LOGKOW/KOWWIN Program found at the following address: http://esc.syrres.com/interkow/interkow.exe. Table E-5 provides the human health data and Table E-6 presents the aquatic toxicity data. When other data related to the toxicity of a chemical were readily available, such data were also reported as "other" toxicity values, which are provided in Table E-7.

For the LFSP, there were 11 chemicals for which both mammalian toxicity and aquatic ecotoxicity data were needed and seven chemicals for which only aquatic ecotoxicity data were needed (mammalian toxicity data were already available from previous projects for those seven chemicals). The remaining chemical inventory for the LFSP constitutes approximately 150 chemicals. Toxicity data from previous projects (e.g., the CDP) were used for those chemicals. The toxicity data used for all potentially toxic chemicals in the LFSP are presented in Table E-1.

Per guidance provided by RAD, ORNL was asked to first search the following sources for toxicity data: IRIS, ATSDR toxicological profiles, HPV challenge robust summaries and supporting documents, and SIDS robust summaries and supporting documents. If data were not found in these sources, Toxline, Medline and TSCATS were to be searched, also per RAD guidance. If data were used from these latter sources, ORNL was instructed to provide robust summaries for data. No data were used from these sources, thus no robust summaries were prepared by ORNL.

In cases where there was more than one data point, ORNL selected a data point based on the applicability of the study to the endpoint of interest and the robustness of the study (as best could be determined from the available data). In many cases, the original sources were not reviewed, but information from secondary sources (e.g., EPA's ECOTOXicology Data Base System [U.S. EPA, 2002]) on the test type and duration were considered. The following hierarchy of fish studies, based on Swanson *et al.* 1997, was employed to choose LC_{50} ecotoxicity data in order of preference:

(1) fathead minnow 96-h flow-through test
(2) 96-h flow-through test for another freshwater fish, excluding trout
(3) fathead minnow 96-h static test
(4) 96-h static test for another freshwater fish, excluding trout

If the only adequate data were for trout, they would also be used. In cases where multiple data points (with equivalent quality, test type, and species type) were available, an average of those data was taken as the data point of interest. This was preferred over taking the most toxic response, as these data are used in relative ranking of chemicals and not to serve as protective exposure limits.

Other aquatic species (e.g., daphnia, algae) were not used in the original methodology used to develop the LCIA toxicity method used in this study (i.e., CHEMS-1, Swanson et al., 1997); however, this does not preclude future versions of this methodology from using other species besides fish, which would represent lower trophic levels (e.g., daphnia or algae).

E.2 GEOMETRIC MEAN DATA FOR CALCULATING TOXICITY HAZARD VALUES

Tables E-8 through E-12 provide the chemical-specific toxicity data used to calculate the geometric means for each toxicity endpoint. Table E-13 provides a summary of the geometric means of each endpoint. The data contributing to the geometric mean calculations were used for previous projects and this project did not attempt to verify each data point. The geometric means are used as the comparative basis for calculating the HVs as described in Sections 3.2.11 through 3.2.13.

E.3 REFERENCES

ACC, et al. 2002. (American Chemistry Council; Propylene Glycol Ether Panel Toxicology Research Task Groups, and CEFIC/Oxygenated Solvents Producers Assoc. Toxicology Support Group). High Production Volume Submission: Test Plan and Robust Studies Summary for Propylene Glycol Ethers Category. December 30, 2002. Submitted to U.S. Environmental Protection Agency.

ACGIH. 2002. (American Conference of Governmental Industrial Hygienists). Threshold limit values and biological exposure indices. ACGIH, Cincinnati, Ohio.

Akzo Nobel. 2002a. MSDS (Material Safety Data Sheet) Ethoduomeen OV/13. Akzo Nobel Surface Chemistry AB, Stenungsund, Sweden. http://www.surfactantseurope.akzonobel.com. Retrieved April, 2003.

Akzo Nobel. 2002b. MSDS (Material Safety Data Sheet) Ethoduomeen T/22. Akzo Nobel Surface Chemistry AB, Stenungsund, Sweden. http://www.surfactantseurope.akzonobel.com. Retrieved April, 2003.

Arena, J.M. 1970. Poisoning: Toxicology, symptoms, treatments. 2nd edition. Springfield, Ill: C.C. Thomas.

Birge, W.J., J.A. Black, and A.G. Westerman. 1979. Evaluation of aquatic pollutants using fish

and amphibian eggs as bioassay organisms. In: Sympos. Animals Monitors Environ. Pollut. 12: 108-118. Nielsen, Migaki, and Scarpelli, (eds.). Storrs, CT. (as cited in ECOTOX).

Camargo, J.A., and J.V. Tarazona, 1991. Short-Term Toxicity of Fluoride Ion (F-) in Soft Water to Rainbow Trout (Salmo gairdneri) and Brown Trout (Salmo trutta fario). Fluoride 24(2):76-83 (as cited in ECOTOX).

Cardwell, R.D., D.G. Foreman, T.R. Payne, and D.J. Wilbur. 1976. Acute toxicity of selected toxicants to six species of fish. EPA-600/3-76-008, U.S. Environmental Protection Agency, Duluth, MN.

Curtis, M. W., T. Copeland, and C. Ward, 1979. Acute Toxicity of 12 Industrial Chemicals to Freshwater and Saltwater Organisms. Water Resources 13(2):137-141 (as cited in ECOTOX).

Dawson, G.W., A.L. Jennings, D. Drozdowski, and E. Rider. 1977. The acute toxicity of 47 industrial chemicals to fresh and saltwater fishes. Jour. Hazard. Mater. 1: 303-318. (as cited in ECOTOX).

Erten-Unal, M., B. Wixson, N. Gale, and J.L. Pitt. 1998. Evaluation of toxicity, bioavailability and speciation of lead, zinc and cadmium in mine/mill wastewaters. Chemical Speciation and Bioavailability 10: 37-46.

Ewell, W.S., J.W. Gorsuch, R.O. Kringle, K.A. Robillard, and R.C. Spiegel. 1986. Simultaneous evaluation of the acute effects of chemicals on seven aquatic species. Environ. Toxicol. Chem. 5: 831-840. (as cited in ECOTOX).

Friberg, L., G.F. Nordberg, E. Kessler, and V.B. Vouk (eds.) 1986. Handbook of the Toxicology of Metals. 2nd. Ed. Vols. I and II. Amsterdam: Elsevier Science Publishers B.V.

Goettl, J.P. Jr., P.H. Davies, and J.R. Sinley. 1976. Water Pollution Studies. In: Colorado Fish Res. Rev. 1972-1975, D.B. Cope, (Ed.). DOW-R-R-F72-75, Colorado Div. Of Wildlife, Boulder, CO. pp. 68-75. (as cited in ECOTOX).

Hagan, E.C., W.H. Hansen, O. Fitzhugh, P. Jenner, et al. 1967. Food flavorings and compounds of related structure. II. Subacute and chronic toxicity. Jour. Food Cosmet. Toxicol. 5: 141-147. (as cited in WHO, 1999).

Holtze, K.E. 1983. Effects of pH and ionic strength on aluminum toxicity to early developmental stages of rainbow trout (*Salmo gairdneri Richardson*). Res. Rep. Ontario Ministry of the Environment, Rexdale, Ont., Canada: 39. (as cited in ECOTOX).

HSDB. 2003. (Hazardous Substances Databank). Bismuth, elemental. TOXNET, National Library of Medicine, National Institute of Health. http://toxnet.nlm.nih.gov. Retrieved April 15, 2003.

Kimball,G. no date given. The effects of lesser known metals and one organic to fathead minnows [*Pimephales promelas*] and *Daphnia magna*. U.S. Environmental Protection Agency, Duluth, MN. (cited in Suter and Tsao, 1996).

Konradova, V. and V. Bencko. 1975. Mechanical damage to rabbit tracheal epithelium from inhaling inert pyrite dust of needle-like structure. Part I. Jour. Hyg. Microbiol. Epidemiol. Immunol. 19:279-285.

Ku, A.Y. and J.M. Schoenung. 2002. Toxicity, Availability and Extraction of the Metals Used in Pb-Free Solders. Presented at UC SMART Workshop, Pb-Free Solder for Electronic, Optical, and MEMS Packaging Manufacturing. University of California, Los Angeles, September 5, 2002.

Landry, T.D. and B.L. Yano. 1984. Dipropylene glycol monomethyl ether: A 13 week inhalation toxicity study in rats and rabbits. Fundam. Appl. Toxicol. 4: 612-617.

Mallinckrodt Baker, Inc. 2001. MSDS (Material Safety Data Sheet) Terpineol. J.T. Baker, from Mallinckrodt Baker, Inc., Phillipsburg, NJ.

NIOSH. 1997. Pocket Guide to Chemical Hazards. U.S. Dept. of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. DHHS Publication No. 97-140. U.S. Govt. Printing Office, Washington, D.C.

Perstorp Specialty Chemicals, 2000. MSDS (Material Safety Data Sheet) Dimethylolpropionic acid. Perstorp Specialty Chemicals AB, Perstorp, Sweden.

Pimentel, R. and R. Bulkley. 1983. Influence of water hardness on fluoride toxicity to rainbow trout. Environ. Toxicol. Chem. 2: 381-386. (as cited in ECOTOX).

Rowe, V.K., D.D. McCollister, H.C. Spencer, et al. 1954. AMA Arch Ind Hyg Occup Med 9: 509-525.

RTECS. 2003a. (Registry of Toxic Effects of Chemical Substances). Zinc Sulfate. RTECS database originally prepared by the National Institute for Occupational Safety and Health (NIOSH), now produced and distributed by MDL Information Systems, Inc., under authority of the U.S. Government.

RTECS. 2003b. (Registry of Toxic Effects of Chemical Substances). Benzo(k)fluoranthene. RTECS database originally prepared by the National Institute for Occupational Safety and Health (NIOSH), now produced and distributed by MDL Information Systems, Inc., under authority of the U.S. Government.

RTECS. 2003c. (Registry of Toxic Effects of Chemical Substances). Fluosilicic Acid. RTECS database originally prepared by the National Institute for Occupational Safety and Health (NIOSH), now produced and distributed by MDL Information Systems, Inc., under authority of the U.S. Government.

Socolof, M.L. J.G. Overly, L.E. Kincaid, J.R. Geibig. 2001. Desktop Computer Displays: A Life-Cycle Assessment, Volumes 1 and 2. U.S. Environmental Protection Agency, EPA 744-R-01-004a,b, 2001. Available at: http://www.epa.gov/oppt/dfe/pubs/comp-dic/lca/).

Smith, L. T. Holsen, N. Ibay, R. Block, and A. De Leon. 1985. Studies on the acute toxicity of fluoride ion to stickleback, fathead minnow, and rainbow trout. Chemosphere 14: 1383-1389. (as cited in ECOTOX).

Spehar, R.L. 1986. Criteria Document Data. Memorandum to D.J. Call, U.S. EPA, Duluth, MN/Center for Lake Superior Environmental Studies, University of Wisconsin-Superior. September 16, 1986. (as cited in ECOTOX).

Stauffer Chemical Co. 1992. Initial Submission: Toxicology lab report on fluosilicic acid with cover letter dated 10/27/92. EPA/OTS; Doc. #88-920010075. (as cited in RTECS, 2000)

Suter, G.W. and C.L. Tsao. 1996. Toxicological benchmarks for screening potential contaminants of concern for effects on aquatic biota: 1996 revision. Risk Assessment Program, Health Sciences Research Division, Oak Ridge National Laboratory. ES/ER/TM-96/R2.

Swanson, M.B., G.A. Davis, L.E. Kincaid, T.W. Schultz, J.E. Bartmess, et al. 1997. "A Screening Method for Ranking and Scoring Chemicals by Potential Human Health and Environmental Impacts," *Environmental Toxicology and Chemistry*, Vol. 16, No. 2, pp. 372-383, SETAC Press.

U.S. CFR. 1994. United States Code of Federal Regulations 29, δ1910.1000. OSHA (Occupational Safety and Health Administration), Dept. of Labor. Occupational safety and health standards.

U.S. CFR. 2002. United States Code of Federal Regulations 40, Part 141.61. National Primary Drinking Water Regulations. Maximum Contaminant Levels for organic contaminants. Environmental Protection Agency, Water Programs.

U.S. Coast Guard, 1984-85. CHRIS – Hazardous Chemical Data. Vol. II. United States Coast Guard, Dept. of Transportation. Washington D.C.: U.S. Govt. Printing Office.

U.S.DHHS. 1995. (United States Department of Health and Human Services). Toxicological profile for polycyclic aromatic hydrocarbons (PAHS), update. Agency for Toxic Substances and Disease Registry, Public Health Service, U.S. DHHS.

U.S. EPA, 2003a. ECOSAR Program. Risk Assessment Division (7403). EPIWIN v. 3.10 (Estimations Programs Interface for Windows), Pollution Prevention Framework. http://www.epa.gov/oppt/p2framework/docs/epiwin.htm. Run on line April, 2003 by Oak Ridge National Laboratory.

U.S. EPA, 2003b. ECOSAR Program. Risk Assessment Division (7403). EPIWIN v. 3.10 (Estimations Programs Interface for Windows), Pollution Prevention Framework. http://www.epa.gov/oppt/p2framework/docs/epiwin.htm. Run on line September, 2003 by U.S. EPA.

U.S. EPA, 2002. ECOTOX User Guide: ECOTOXicology Database System. Version 3.0. Available: http:/www.epa.gov/ecotox/. Retrieved online April, 2003.

U.S. EPA, 1998a. Printed Wiring Board Cleaner Technologies Substitutes Assessment: Making Holes Conductive. Chapter Three. Design for the Environment. EPA 744R-98-004a and EPA 744R-98-004b.

U.S. EPA, 1998b. Integrated Risk Information System (IRIS). Zinc and Compounds. Office of Research and Development, National Center for Environmental Assessment, U.S. Environmental Protection Agency. http://www.epa.gov/iris/. Retrieved online April, 2003.

U.S. EPA, 1997. Integrated Risk Information System (IRIS). Benzo[k]fluoranthene. Office of Research and Development, National Center for Environmental Assessment, U.S. Environmental Protection Agency. http://www.epa.gov/iris/. Retrieved online April, 2003.

U.S.EPA, 1996. Cleaner Technologies Substitutes Assessment, A Methodology and Resource Guide. Chapter 5. Chemical and process information. Environmental hazards summary, p. 5-59. Pollution Prevention Information Clearinghouse (PPIC), U.S. Environmental Protection Agency, Washington, D.C., Decmeber.

U.S. EPA, 1994. Estimated Aquatic Toxicity Values, Screen Reclamation Chemicals. Draft Cleaner Technologies Substitutes Assessment (CTSA): Screen Reclamation, Chapter Two. Design for the Environment. EPA 744R-94-005a, September 1994.

U.S. EPA, 1993. Provisional Guidance for Quantitative Risk Assessment of Polycyclic Aromatic Hydrocarbons. EPA/600/R-93/089. United States Environmental Protection Agency.

USGS/CERC. 2003. (U.S. Geological Survey; Columbia Environmental Research Center, Columbia Missouri). Acute toxicity database. Biological Resources Division, Central Region, Columbia Environmental Research Center.
LINK"http://sss.cerc.usgs.gov/"http://www.cerc.usgs.gov/. Retrieved online April, 2003.

Van der Hoeven, J.C., and G.T. Welboren. 1987. Assessment of the acute toxicity of Dowanol-DPnB in *Poecilia reticulata*. NOTOX Report No. not reported. July 1987. Unpublished report.

Weiss, G. 1980. Hazardous Chemicals Data Book. Fluosilicic Acid. G. Weiss (ed.) Park Ridge, NJ: Noyes Data Corporation. p. 474.

WHO, 1999. WHO Food Additives Series: 42. Aliphatic acyclic and alicyclic terpenoid tertiary alcohols and structurally related substances. International Programme on Chemical Safety, World Health Organization, Safety Evaluation of Certain Food Additives. Prepared by the Fifty-first meeting of the Joint FAO/WHO Expert Committee on Food Additives (JECFA). Geneva, Switzerland.

Wilde, E.W., R. Soracco, L. Mayack, R. Shealy, et al. 1983a. Comparison of chlorine and chlorine dioxide toxicity to fathead minnows and bluegill. Water Res. 17: 1327-1331. (as cited in ECOTOX).

Wilde, E.W., R. Soracco, L. Mayack, R. Shealy, and T. Broadwell, 1983b. Acute Toxicity of Chlorine and Bromine to Fathead Minnows and Bluegills. Bull. Environ. Contam. Toxicol. 31(3):309-314 (as cited in ECTOX).

E.4 GLOSSARY OF TOXICITY COMPARISON TERMS

CC (Concentration of concern)
Calculated aquatic toxicity value derived by dividing the lowest chronic value in mg/L by ten.

EC50 (Effective Concentration 50)
A calculated dose of a substance which is expected to cause an effect on 50% of a defined animal population.

LDLo (Lethal Dose Low)
The lowest dose (other than LD50) of a substance introduced by any route, other than inhalation, over any given period of time in one or more divided portions and reported to have caused death in humans or animals.

LD50 (Lethal Dose 50)
A calculated dose of a substance which is expected to cause the death of 50% of a defined experimental animal population.

LC50 (Lethal Concentration 50)
A calculated concentration of a substance in air or water, which is expected to cause the death of 50% of a defined experimental animal population.

LOAEL (Lowest observable adverse effect level)

MCL (Maximum Contaminant Level)

The highest level of a contaminant that is allowed in drinking water. It is a national primary drinking water regulation established by EPA.

NOEL (No observable effect level)

NOAEL (No observable adverse effect level)

OEL (Occupational exposure limit)
The concentration of a substance in air, that a worker may safely be exposed to on a regular basis, usually for an 8 hour workday.

PEF (Potency equivalency factor)
A calculated carcinogenicity comparison of a substance, relative to (in this case benzo(a)pyrene) another substance.

PEL (Permissible exposure limit)
The 8-hour time weighted average for the concentration of a substance in air that must not be exceeded during any 8-hour workshift of a 40 hour work week.

TDLo (Toxic Dose Low)
The lowest dose of a substance reported to produce any toxic effect in humans or tumorigenic, reproductive, or multiple effects in animals.

TLm (Median tolerance limit)
A calculated dose which is expected to cause an effect (includes death) in 50% of a test population.

WOE (Weight of evidence)
Classification of relevance and quality of studies used to make a determination of carcinogenicity.

Table E-1. Toxicity data for potentially toxic LFSP chemicals

Cas #	Material (flow)	oral SF (mg/kg- day)[1]	inhal SF (mg/kg- day)$^{-1}$	WOE (EPA & IARC) (a)	oral NOAEL (b) (mg/kg-day)	inhal NOAEL (b) (mg/m^3)	oral LOAEL (b,c) (mg/kg-day)	inhal LOAEL (b,c) (mg/m^3)	fish LC_{50} (mg/L)	fish NOEL (mg/L)
1746-01-6	2,3,7,8-TCDD (2,3,7,8-Tetrachlorodibenzo-p-Dioxin)	1.50E+05	1.50E+05	1	9.00E-08	X	X	X	XX	XX
51207-31-9	2,3,7,8-TCDF (2,3,7,8-Tetrachlorodibenzo Furan)	1.50E+04	1.50E+04	3	- -	- -	- -	- -	XX	XX
121-14-2	2,4-Dinitrotoluene	0.68	X	B2	0.2	X	X	X	24	6
91-57-6	2-Methylnaphthalene	- -	- -	- -	- -	- -	- -	- -	XX	XX
56-49-5	3-Methylcholanthrene	- -	- -	- -	X	X	2.86	X	XX	XX
3697-24-3	5-Methyl chrysene (category: PAH)	X	- -	2B	- -	- -	- -	- -	XX	XX
83-32-9	Acenaphthene (category: PAH)	- -	- -	- -	175	X	350	X	XX	XX
208-96-8	Acenaphthylene (category: PAH)	X	- -	D	- -	- -	- -	- -	XX	XX
75-07-0	Ethanal (Acetaldehyde)	X	7.70E-03	2B	125	300	X	X	34	9
64-19-7	Acetic acid	- -	- -	- -	195	X	X	X	XX	XX
67-64-1	Acetone	X	- -	D	100	X	X	X	720	180
98-86-2	Acetophenone	- -	- -	- -	423	X	X	X	XX	XX
107-02-8	Acrolein	X	- -	C,3	- -	- -	- -	- -	XX	XX
No CAS #	Aluminium (Al3+)	- -	- -	- -	- -	- -	- -	- -	3.6	0.36
7429-90-5	Aluminum (Al)	X	- -	SAR0	60	X	X	X	11	3.3
7664-41-7	Ammonia	- -	- -	- -	34	40	X	X	2	9.00E-02
6484-52-2	Ammonium nitrate									
120-12-7	Anthracene (category: PAH)	X	- -	SAR1	1000	X	X	X	0.01	- -
7440-36-0	Antimony (Sb)	- -	- -	- -	X	X	0.35	X	14.4	1.6
7440-38-2	Arsenic (As)	1.5	50	A	8.00E-04	X	X	X	14.4	2.1
7440-39-3	Barium (Ba)	- -	- -	- -	0.21	X	X	X	580	50
20-02-0	Barium compounds [Barium (Ba++)]	X	- -	D	0.21	X	X	X	200	10
71-43-2	Benzene	0.055	0.029	A,1	1	1.15	10	98	19	4
56-55-3	Benzo{a}anthracene (category: PAH)	0.73	0.31	B2	- -	- -	- -	- -	XX	XX
50-32-8	Benzo{a}pyrene	7.3	3.1	B2,2A	- -	- -	- -	- -	XX	XX
56832-73-6	Benzo{b,j,k}fluoranthene (category: PAH)	X	- -	B2	- -	- -	- -	- -	XX	XX
205-99-2	Benzo{b}fluoranthene	0.73	0.31	B2	- -	- -	- -	- -	XX	XX
191-24-2	Benzo{g,h,I}perylene (category: PAH)	X	- -	D	- -	- -	- -	- -	XX	XX
207-08-9	Benzo{k}fluoranthene	--	--	B2	--	--	--	--	1000	0.006
100-44-7	Benzyl chloride	0.17	X	B2,3	- -	- -	- -	- -	XX	XX
7440-41-7	Beryllium (Be)	4.3	8.4	X	X	X	X	5.50E-04	2	0.2
117-81-7	Bis(2-ethylhexyl)phthalate [Di(2-ethylhexyl)phthalate]	X	X	B2,2B	50	50	X	X	1	0.08
7440-69-9	Bismuth	--	--	--	3,243	--	--	--	5	0.5
1303-96-4	Borax	- -	- -	- -	- -	- -	- -	- -	XX	XX
No CAS #	Boron (B III)	- -	- -	- -	8.8	X	X	X	113	27
7440-42-8	Boron (B)	- -	- -	- -	8.8	X	X	X	113	27

Table E-1. Toxicity data for potentially toxic LFSP chemicals

Cas #	Material (flow)	oral SF (mg/kg- day)^{1}	inhal SF (mg/kg- day)$^{-1}$	WOE (EPA & IARC) (a)	oral NOAEL (b) (mg/kg-day)	inhal NOAEL (b) (mg/m^3)	oral LOAEL (b,c) (mg/kg-day)	inhal LOAEL (b,c) (mg/m^3)	fish LC_{50} (mg/L)	fish NOEL (mg/L)
7726-95-6	Bromine	- -	- -	- -	- -	- -	- -	- -	XX	XX
75-25-2	Bromoform	7.90E-03	3.90E-03	B2	17.9	X	X	X	XX	XX
7440-43-9	Cadmium (Cd)	X	6.1	B1,1	X	X	4.00E-02	2.20E-02	0.001	0.001
20-04-2	Cadmium cmpds (as CdCl2) [Cadmium (Cd++)]	X	- -	B1,2A	5.00E-03	X	X	X	0.1	- -
75-15-0	Carbon disulfide	- -	- -	- -	X	10	X	X	694	174
630-08-0	Carbon monoxide (CO)	- -	- -	- -	X	114.5	X	55	XX	XX
75-69-4	CFC 11 (Trichlorofluoromethane)	- -	- -	- -	X	X	349	X	XX	XX
76-14-2	CFC 114 (1,2-dichlorotetrafluoroethane)	- -	- -	- -	2.73E+02	X	X	X	XX	XX
75-71-8	CFC 12 (Dichlorodifluoromethane)	- -	- -	- -	15	X	X	X	XX	XX
75-72-9	CFC 13 (Dichlorotrifluoromethane)	- -	- -	- -	- -	- -	- -	- -	XX	XX
7782-50-5	Chlorine (Cl2)	- -	- -	- -	14	X	X	X	0.34	0.02
1341-24-8	Chloroacetophenone	- -	- -	- -	- -	- -	- -	- -	XX	XX
108-90-7	Chlorobenzene	X	- -	SAR0	12.5	377	X	X	17	2
16065-83-1	Chromium (Cr III)	X	- -	D	1468	X	X	X	3.3	0.33
7440-47-3	Chromium (Cr)	X	- -	1	- -	- -	- -	- -	52	5.2
18540-29-9	Chromium, hexavalent (Cr VI)	X	41	A,1	2.5	X	X	X	22.6	2.23
218-01-9	Chrysene (category: PAH)	7.30E-03	3.10E-03	X	- -	- -	- -	- -	XX	XX
7440-48-4	Cobalt (Co)	- -	- -	- -	- -	- -	- -	- -	XX	XX
7440-50-8	Copper (Cu)	X	- -	D	5.30E-01	X	X	X	1.40E-02	4.00E-03
No CAS #	Copper (Cu+, Cu++)	- -	- -	- -	5.30E-01	X	X	X	1.40E-02	4.00E-03
98-82-8	Cumene	X	- -	SAR0	154	537	X	X	6	0.49
57-12-5	Cyanide (CN)	X	- -	D	10.8	X	X	X	56	5.7
53-70-3	Dibenzo{a,h}anthracene	7.3	3.1	B2	- -	- -	- -	- -	XX	XX
25321-22-6	Dichlorobenzene (mixed isomers)	X	X	SAR0	X	610.4	X	X	1	0.05
107-06-2	Ethylene dichloride (Dichloroethane)	9.10E-02	9.10E-02	B2,2B	18	221	X	X	136	34
75-09-2	Dichloromethane (Methylene chloride)	7.50E-03	1.65E-03	B2,2B	155	796	X	X	330	83
77-78-1	Dimethyl sulfate	X	X	B1,2A	- -	- -	- -	- -	XX	XX
57-97-6	Dimethylbenzanthracene	- -	- -	- -	X	X	X	1.40E-02	XX	XX
74-84-0	Ethane	- -	- -	- -	- -	- -	- -	- -	XX	XX
75-00-3	Ethyl chloride	X	X	3	X	3600	X	X	16	4
100-41-4	Ethylbenzene	X	X	SAR0	136	2370	X	X	11	1
106-93-4	Ethylene dibromide	85	7.60E-01	B2	- -	- -	- -	- -	XX	XX
206-44-0	Fluoranthene (category: PAH)	X	X	D	125	X	X	X	XX	XX
86-73-7	Fluorene (category: PAH)	X	X	D	125	X	X	X	XX	XX
16984-48-8	Fluoride	- -	- -	- -	- -	- -	- -	- -	- -	- -
No CAS #	Fluorides (F-)	- -	- -	- -	6.00E-02	X	X	X	- -	- -

Table E-1. Toxicity data for potentially toxic LFSP chemicals

Cas #	Material (flow)	oral SF (mg/kg- day)[1]	inhal SF (mg/kg- day)$^{-1}$	WOE (EPA & IARC) (a)	oral NOAEL (b) (mg/kg-day)	inhal NOAEL (b) (mg/m^3)	oral LOAEL (b,c) (mg/kg-day)	inhal LOAEL (b,c) (mg/m^3)	fish LC_{50} (mg/L)	fish NOEL (mg/L)
7782-41-4	Fluorine (F2)	- -	- -	- -	6.00E-02	X	X	X	100	10
16872-11-0	Fluoroboric acid	--	--	--	--	--	0.77	--	1000	20
16961-83-4	Fluorosilicic acid	--	--	--	--	--	0.77	--	100	10
(d)	Flux A (d)	--	--	--	--	--	--	--	900	90
(d)	Flux B (d)	--	--	--	450	200	1000	810	930	100
(d)	Flux C (d)	- -	- -	- -	- -	- -	- -	- -	XX	XX
(d)	Flux D (d)	--	--	--	--	--	--	--	0.5	0.05
(d)	Flux E (d)	--	--	--	--	--	--	--	1000	100
(d)	Flux F (d)	--	--	--	--	--	--	--	1000	100
50-00-0	Formaldehyde (CH2O)	X	4.50E-02	B1,2A	15	0.6	X	X	24	6
No CAS #	Light Fuel Oil (#2, distillate and diesel)	- -	- -	- -	- -	- -	- -	- -	XX	XX
75-63-8	Halon 1301	- -	- -	- -	- -	- -	- -		XX	XX
75-45-6	HCFC 22 (Chlorodifluoromethane)	- -	- -	- -	X	5,260	X	X	XX	XX
110-54-3	Hexane	- -	- -	- -	X	X	X	73	2.5	0.25
7647-01-0	Hydrochloric acid	X	X	3	X	15	X	X	19	0.95
7664-39-3	Hydrofluoric acid (Hydrogen fluoride)	- -	- -	- -	- -	- -	- -	- -	265	13
74-90-8	Hydrogen Cyanide	X	X	SAR0	10.8	X	30	7.07	1,385	346
7783-06-4	Hydrogen Sulfide	- -	- -	- -	3.1	X	X	15	XX	XX
193-39-5	Indeno{1,2,3-cd}pyrene (category: PAH)	7.30E-01	3.10E-01	B2	- -	- -	- -	- -	XX	XX
1309-36-0	Iron pyrite	--	--	--	--	1	--	--	1000	--
78-59-1	Isophorone	9.50E-04	X	C	150	X	X	X	XX	XX
67-63-0	Isopropyl alcohol	X	X	1	230	268.3	X	X	8,623	2,156
7439-92-1	Lead (Pb)	X	X	B2,2B			0.014	0.011	31.5	0.004
20-11-1	Lead compounds (as PbCl2) [Lead (Pb++, Pb4+)]	X	X	B2,2B		- -	0.014	0.011	5	0.26
NA	Liquified petroleum gas (LPG)	- -	- -	- -	- -	- -	- -	- -	2600	260
7439-96-5	Manganese	X	X	D	0.14	X	X	0.15	- -	- -
	Mercaptan									
7439-97-6	Mercury (Hg)	X	X	D,3	X	6.00E-03	X	9.00E-03	0.155	0.005
no CAS#	Mercury cmpds (as HgCl2) [Mercury (Hg+, Hg++)]	X	X	C	X	X	0.226	X	0.155	0.005
	Metals, unspecified									
74-82-8	Methane (natural gas)	- -	- -	- -	- -	- -	- -	- -	XX	XX
67-56-1	Methanol	X	X	SAR0	500	130	X	X	29,400	7,350
74-83-9	Methyl bromide (bromomethane)	X	- -	C,3	0.4	4.3	X	X	11	3
74-87-3	Methyl chloride (Chloromethane)	1.30E-02	6.30E-03	C,3	X	1138.4	X	1550	550	138
78-93-3	Methyl ethyl ketone	X	X	D	125	8047	X	X	3,220	805
60-34-4	Methyl hydrazine	3	17.2	A3	- -	- -	- -	- -	XX	XX

Table E-1. Toxicity data for potentially toxic LFSP chemicals

Cas #	Material (flow)	oral SF (mg/kg- day)^{1}	inhal SF (mg/kg- day)$^{-1}$	WOE (EPA & IARC) (a)	oral NOAEL (b) (mg/kg-day)	inhal NOAEL (b) (mg/m^3)	oral LOAEL (b,c) (mg/kg-day)	inhal LOAEL (b,c) (mg/m^3)	fish LC_{50} (mg/L)	fish NOEL (mg/L)
80-62-6	Methyl methacrylate	X	X	SAR0	7.5	111.7	X	X	259	65
1634-04-4	Methyl tert butyl ether (MTBE)	X	X	SAR0	100	2880	X	X	786	197
7439-98-7	Molybdenum (Mo)	- -	- -	- -	X	X	0.14	X	157	0.125
91-20-3	Naphthalene	X	X	C	71	X	X	9.3	6	0.59
7440-02-0	Nickel (Ni)	X	X	A	5	X	X	X	2.48	0.09
20-14-4	Nickel cmpds (as NiCl2) [Nickel (Ni++, Ni3+)]	X	X	A,1	- -	- -	- -	- -	27	1
14797-55-8	Nitrates	- -	- -	- -	1.6	X	X	X	2,213	213
no CAS#	Nitrogen Oxides (NOx)	- -	- -	- -	- -	- -	- -	- -	XX	XX
10024-97-2	Nitrous oxide	- -	- -	- -	- -	- -	- -	- -	XX	XX
NA	Particulate matter (PM-10) [Particulates < 10 microns]	- -	- -	- -	- -	- -	- -	- -	XX	XX
NA	Particulate matter, total (PM)	- -	- -	- -	- -	- -	- -	- -	XX	XX
109-66-0	Pentane	X	X	D	- -	- -	- -	- -	XX	XX
85-01-8	Phenanthrene (category: PAH)	X	X	D	- -	- -	- -	- -	XX	XX
108-95-2	Phenol	X	X	D,3	60	X	X	X	34	8
7723-14-0	Phosphorus	X	X	D	1.50E-02	X	X	X	0.02	- -
123-38-6	Propionaldehyde	X	X	SAR3	X	200	X	X	44	11
115-07-1	Propylene (Propene)	X	X	SAR0	X	9375	X	X	5	1
129-00-0	Pyrene (category: PAH)	X	X	D	75	X	X	X	XX	XX
7440-20-2	Scandium (Sc)	- -	- -	- -	- -	- -	- -	- -	XX	XX
7782-49-2	Selenium (Se)	X	X	D	1.50E-02	X	X	X	4.9	0.1
7440-21-3	Silicon (Si)	- -	- -	- -	- -	- -	- -	- -	XX	XX
7440-22-4	Silver	X	X	D	X	X	1.40E-02	X	4.00E-03	0.001
7681-52-9	Sodium Hypochlorite	X	X	3	2.1	X	X	X	0.53	0.05
7440-24-6	Strontium (Sr)	- -	- -	- -	190	X	X	X	210	20
100-42-5	Styrene	X	X	C,2B	100	565	X	X	4	0.44
7446-09-5	Sulfur dioxide	X	X	3	X	0.104	X	X	XX	XX
no CAS#	Sulfur oxides (SOx)	- -	- -	- -	- -	- -	- -	- -	XX	XX
7664-93-9	Sulfuric acid	X	X	1	X	0.1	X	X	31	2
127-18-4	Tetrachloroethylene (Perchloroethylene)	5.20E-02	2.00E-03	B2,2B	14	740.2	X	X	17	2
7440-28-0	Thallium (TI)	- -	- -	- -	- -	- -	- -	- -	XX	XX
7440-31-5	Tin (Sn)	- -	- -	- -	- -	- -	- -	- -	626	62.6
7440-32-6	Titanium	X	X	C	X	0.8	1146	X	- -	- -
108-88-3	Toluene	X	X	D,3	100	411.1	X	X	34	4
71-55-6	Trichloroethane (1,1,1-trichloroethane)	- -	- -	- -	2.50E+02	1.21E+03	X	X	48	7
67-66-3	Trichloromethane (Chloroform)	6.10E-03	8.10E-02	B2,2B	X	X	12.9	X	71	18
7440-62-2	Vanadium (V)	- -	- -	- -	3.00E-03	X	X	X	4	0.67

Table E-1. Toxicity data for potentially toxic LFSP chemicals

Cas #	Material (flow)	oral SF (mg/kg- day)[1]	inhal SF (mg/kg- day)$^{-1}$	WOE (EPA & IARC) (a)	oral NOAEL (b) (mg/kg-day)	inhal NOAEL (b) (mg/m^3)	oral LOAEL (b,c) (mg/kg-day)	inhal LOAEL (b,c) (mg/m^3)	fish LC_{50} (mg/L)	fish NOEL (mg/L)
108-05-4	Vinyl acetate	X	X	SAR0	100	176	X	X	100	25
1330-20-7	Xylene (C24H30) [mixed isomers]	X	X	D	179	X	X	X	13	1
7440-66-6	Zinc (Zn)	X	X	D	0.9	X	1	X	9.00E-02	0.036
No CAS #	Zinc (Zn++)	- -	- -	- -	- -	- -	- -	- -	14	0.8
7733-02-0	Zinc sulfate	--	--	D	--	--	1	--	1.27	--
Key:										
(a)=See Table 3-72 in Section 3.2.11.1 for a description of WOE classifications.										
(b)=Only lowest value of the NOAEL (or LOAEL/10) is used to calculate chronic, non-cancer effects.										
(c)=LOAEL only needed if no NOAEL found.										
(d)=Flux material names and CAS#s have been withheld to protect confidentiality.										
XX=Aquatic toxicity data not needed because there are no waterborne releases of this chemical in the LFSP inventories.										
X=Data not needed because other data are provided to calculate impact score (e.g., LOAEL not needed if NOAEL provided, and WOE used if SF not available).										
SAR0=Not a probable carcinogen based on structure-activity relationship (SAR) evaluation.										
SAR1=Possible carcinogen based on SAR evaluation.										
- - =No data available, defaulted to mean hazard value (see Section 3.1.2.12 for an explanation of hazard values).										
Sources:										
Oral and inhalation slope factors (SF): Integrated Risk Information System (IRIS) or Health Effects Assessment Summary Tables (HEAST) (EPA, 1994) as cited in Risk										
Assessment Information System (RAIS): http://risk.lsd.ornl.gov/rap_hp.shtml.										
Weight of Evidence (WOE): IRIS Web site (http://www.epa.gov/IRIS).										
Oral no observable adverse effect level (NOAEL), inhalation NOAEL, oral lowest obserable adverse effect level (LOAEL) and inhalation LOAEL:										
IUCLID, 1996; HEAST, 1994; Kincaid and Geibig, 1998; EPA, 2000a; SRC, 2000; EPA, 2000b; Geibig and Swanson, 2000; Sax and Lewis, 1987; NIOSH, 1978; EPA, 1984;										
and EPA, 1987.										
Fish LC50 and fish NOAEL: EPA, 2001; HSDB; Davis et al. 1994, Appendix E; and Geiger et al., 1984, 1985, 1986, 1988, 1990.										
Sources associated with data collected from ORNL (May, 2003) are listed in this Appendix under the References Section E.3.										

Table E-2. Toxicity hazard values (HV) for potentially toxic chemicals in the LFSP

CAS#	Material (flow)	Cancer HV	Non-cancer HV	Aquatic ecotoxicity HV
1746-01-6	2,3,7,8-TCDD (2,3,7,8-Tetrachlorodibenzo-p-Dioxin)	2.11E+05	1.56E+08	not searched
51207-31-9	2,3,7,8-TCDF (2,3,7,8-Tetrachlorodibenzo Furan)	2.11E+04	1.00E+00	not searched
121-14-2	2,4-Dinitrotoluene	9.58E-01	7.00E+01	1.68E+00
91-57-6	2-Methylnaphthalene	1.00E+00	1.00E+00	not searched
56-49-5	3-Methylcholanthrene	1.00E+00	4.90E+01	not searched
3697-24-3	5-Methyl chrysene (category: PAH)	1.00E+00	1.00E+00	not searched
83-32-9	Acenaphthene (category: PAH)	1.00E+00	8.00E-02	not searched
208-96-8	Acenaphthylene (category: PAH)	0.00E+00	1.00E+00	not searched
75-07-0	Ethanal (Acetaldehyde)	4.53E-03	2.29E-01	1.16E+00
64-19-7	Acetic acid	1.00E+00	7.18E-02	not searched
67-64-1	Acetone	0.00E+00	1.40E-01	5.58E-02
98-86-2	Acetophenone	1.00E+00	3.31E-02	not searched
107-02-8	Acrolein	1.00E+00	1.00E+00	not searched
No CAS #	Aluminium (Al3+)	1.00E+00	1.00E+00	1.77E+01
7429-90-5	Aluminum (Al)	0.00E+00	2.33E-01	3.42E+00
7664-41-7	Ammonia	1.00E+00	1.72E+00	5.56E+01
120-12-7	Anthracene (category: PAH)	1.00E+00	1.40E-02	8.88E+03
7440-36-0	Antimony (Sb)	1.00E+00	4.00E+02	4.15E+00
7440-38-2	Arsenic (As)	2.94E+01	1.75E+04	3.57E+00
7440-39-3	Barium (Ba)	1.00E+00	6.67E+01	1.20E-01
20-02-0	Barium compounds [Barium (Ba++)]	0.00E+00	6.67E+01	5.13E-01
71-43-2	Benzene	7.75E-02	5.97E+01	2.27E+00
56-55-3	Benzo{a}anthracene (category: PAH)	1.03E+00	1.00E+00	not searched
50-32-8	Benzo{a}pyrene	1.03E+01	1.00E+00	not searched
56832-73-6	Benzo{b,j,k}fluoranthene (category: PAH)	1.00E+00	1.00E+00	not searched
205-99-2	Benzo{b}fluoranthene	1.03E+00	1.00E+00	not searched
191-24-2	Benzo{g,h,I}perylene (category: PAH)	0.00E+00	1.00E+00	not searched
207-08-9	benzo{k}fluoranthene	1.00E+00	1.00E+00	6.50E+02
100-44-7	Benzyl chloride	2.39E-01	1.00E+00	not searched
7440-41-7	Beryllium (Be)	6.06E+00	1.25E+06	3.18E+01
117-81-7	Bis(2-ethylhexyl)phthalate [Di(2-ethylhexyl)phthalate]	1.00E+00	1.37E+00	7.34E+01
7440-69-9	Bismuth	1.00E+00	4.32E-03	1.27E+01
1303-96-4	Borax	1.00E+00	1.00E+00	not searched
No CAS #	Boron (B III)	1.00E+00	1.59E+00	3.62E-01
7440-42-8	Boron (B)	1.00E+00	1.59E+00	3.62E-01
7726-95-6	Bromine	1.00E+00	1.00E+00	not searched
75-25-2	Bromoform	1.11E-02	7.82E-01	not searched
No CAS #	BSA (bismuth-tin-silver) alloy*	9.90E-01	1.00E+02	not searched
7440-43-9	Cadmium (Cd)	3.59E+00	3.12E+04	2.85E+04
20-04-2	Cadmium cmpds (as CdCl2) [Cadmium (Cd++)]	1.00E+00	2.80E+03	2.47E+02
75-15-0	Carbon disulfide	1.00E+00	6.87E+00	5.79E-02
630-08-0	Carbon monoxide (CO)	1.00E+00	6.00E-01	not searched
75-69-4	CFC 11 (Trichlorofluoromethane)	1.00E+00	4.01E-01	not searched
76-14-2	CFC 114 (1,2-dichlorotetrafluoroethane)	1.00E+00	5.13E-02	not searched
75-71-8	CFC 12 (Dichlorodifluoromethane)	1.00E+00	9.33E-01	not searched
75-72-9	CFC 13 (Dichlorotrifluoromethane)	1.00E+00	1.00E+00	not searched

Table E-2. Toxicity hazard values (HV) for potentially toxic chemicals in the LFSP

CAS#	Material (flow)	Cancer HV	Non-cancer HV	Aquatic ecotoxicity HV
7782-50-5	Chlorine (Cl2)	1.00E+00	1.00E+00	2.67E+02
1341-24-8	Chloroacetophenone	1.00E+00	1.00E+00	not searched
108-90-7	Chlorobenzene	0.00E+00	1.12E+00	3.40E+00
16065-83-1	Chromium (Cr III)	0.00E+00	9.54E-03	1.93E+01
7440-47-3	Chromium (Cr)	1.00E+00	1.00E+00	1.22E+00
18540-29-9	Chromium, hexavalent (Cr VI)	2.41E+01	5.60E+00	2.84E+00
218-01-9	Chrysene (category: PAH)	1.03E-02	1.00E+00	not searched
7440-48-4	Cobalt (Co)	1.00E+00	1.00E+00	not searched
7440-50-8	Copper (Cu)	0.00E+00	2.64E+01	2.73E+03
No CAS #	Copper (Cu+, Cu++)	1.00E+00	2.64E+01	2.73E+03
98-82-8	Cumene	0.00E+00	1.28E-01	1.21E+01
57-12-5	Cyanide (CN)	0.00E+00	1.30E+00	1.12E+00
53-70-3	Dibenzo{a,h}anthracene	1.03E+01	1.00E+00	not searched
25321-22-6	Dichlorobenzene (mixed isomers)	0.00E+00	1.13E-01	1.03E+02
107-06-2	Ethylene dichloride (Dichloroethane)	1.28E-01	7.78E-01	2.96E-01
75-09-2	Dichloromethane (Methylene chloride)	1.06E-02	9.03E-02	1.22E-01
77-78-1	Dimethyl sulfate	1.00E+00	1.00E+00	not searched
57-97-6	Dimethylbenzanthracene	1.00E+00	4.91E+04	not searched
74-84-0	Ethane	1.00E+00	1.00E+00	not searched
75-00-3	Ethyl chloride	0.00E+00	1.91E-02	2.51E+00
100-41-4	Ethylbenzene	0.00E+00	1.03E-01	6.14E+00
106-93-4	Ethylene dibromide	1.20E+02	1.00E+00	not searched
206-44-0	Fluoranthene (category: PAH)	0.00E+00	1.12E-01	not searched
86-73-7	Fluorene (category: PAH)	0.00E+00	1.12E-01	not searched
16984-48-8	Fluoride	1.00E+00	1.00E+00	2.00E+00
No CAS #	Fluorides (F-)	1.00E+00	2.33E+02	2.00E+00
7782-41-4	Fluorine (F2)	1.00E+00	2.33E+02	6.36E-01
16872-11-0	Fluoroboric acid	1.00E+00	1.82E+02	2.20E-01
16961-83-4	Fluorosilicic acid	1.00E+00	1.82E+02	6.36E-01
(d)	Flux A (d)	1.00E+00	1.00E+00	7.07E-02
(d)	Flux B (d)	1.00E+00	3.43E-01	6.55E-02
(d)	Flux C (d)	1.00E+00	1.00E+00	1.00E+00
(d)	Flux D (d)	1.00E+00	1.00E+00	1.27E+02
(d)	Flux E (d)	1.00E+00	1.00E+00	6.36E-02
(d)	Flux F (d)	1.00E+00	1.00E+00	6.36E-02
50-00-0	Formaldehyde (CH2O)	2.65E-02	1.14E+02	1.68E+00
No CAS #	Fuel Oil, light (#2, distillate and diesel)	1.00E+00	1.00E+00	not searched
75-63-8	Halon 1301	1.00E+00	1.00E+00	not searched
75-45-6	HCFC 22 (Chlorodifluoromethane)	1.00E+00	1.31E-02	not searched
110-54-3	Hexane	1.00E+00	9.41E+00	2.54E+01
7647-01-0	Hydrochloric acid	0.00E+00	4.58E+00	5.40E+00
7664-39-3	Hydrofluoric acid (Hydrogen fluoride)	1.00E+00	1.00E+00	3.93E-01
74-90-8	Hydrogen Cyanide	0.00E+00	1.30E+00	2.90E-02
7783-06-4	Hydrogen Sulfide	1.00E+00	4.52E+00	not searched
193-39-5	Indeno{1,2,3-cd}pyrene (category: PAH)	1.03E+00	1.00E+00	not searched
1309-36-0	Iron pyrite	1.00E+00	6.87E+01	1.03E-01

Table E-2. Toxicity hazard values (HV) for potentially toxic chemicals in the LFSP

CAS#	Material (flow)	Cancer HV	Non-cancer HV	Aquatic ecotoxicity HV
78-59-1	Isophorone	1.34E-03	9.33E-02	not searched
67-63-0	Isopropyl alcohol	1.00E+00	2.56E-01	4.66E-03
7439-92-1	Lead (Pb)	1.00E+00	6.24E+04	9.76E+02
20-11-1	Lead compounds (as PbCl2) [Lead (Pb++, Pb4+)]	1.00E+00	6.24E+04	1.99E+01
No CAS #	Liquified petroleum gas (LPG)	1.00E+00	1.00E+00	2.45E-02
7439-96-5	Manganese	0.00E+00	1.00E+02	2.00E+00
7439-97-6	Mercury (Hg)	0.00E+00	1.14E+04	9.39E+02
no CAS#	Mercury cmpds (as HgCl2) [Mercury (Hg+, Hg++)]	1.00E+00	6.19E+02	9.39E+02
74-82-8	Methane (natural gas)	1.00E+00	1.00E+00	not searched
67-56-1	Methanol	0.00E+00	5.28E-01	1.37E-03
74-83-9	Methyl bromide (bromomethane)	1.00E+00	3.50E+01	3.54E+00
74-87-3	Methyl chloride (Chloromethane)	1.83E-02	6.03E-02	7.30E-02
78-93-3	Methyl ethyl ketone	0.00E+00	1.12E-01	1.25E-02
60-34-4	Methyl hydrazine	1.01E+01	1.00E+00	not searched
80-62-6	Methyl methacrylate	0.00E+00	1.87E+00	1.55E-01
1634-04-4	Methyl tert butyl ether (MTBE)	0.00E+00	1.40E-01	5.11E-02
7439-98-7	Molybdenum (Mo)	1.00E+00	1.00E+03	3.14E+01
91-20-3	Naphthalene	1.00E+00	1.97E-01	1.07E+01
7440-02-0	Nickel (Ni)	1.00E+00	2.80E+00	5.33E+01
20-14-4	Nickel cmpds (as NiCl2) [Nickel (Ni++, Ni3+)]	1.00E+00	1.00E+00	4.81E+00
14797-55-8	Nitrates	1.00E+00	8.75E+00	2.94E-02
no CAS#	Nitrogen Oxides (NOx)	1.00E+00	1.00E+00	not searched
10024-97-2	Nitrous oxide	1.00E+00	1.00E+00	not searched
NA	Particulate matter (PM-10) [Particulates < 10 microns]	1.00E+00	1.00E+00	not searched
NA	Particulate matter, total (PM)	1.00E+00	1.00E+00	not searched
109-66-0	Pentane	0.00E+00	1.00E+00	not searched
85-01-8	Phenanthrene (category: PAH)	0.00E+00	1.00E+00	not searched
108-95-2	Phenol	0.00E+00	2.33E-01	1.21E+00
7723-14-0	Phosphorus	0.00E+00	9.33E+02	5.13E+03
123-38-6	Propionaldehyde	1.00E+00	3.43E-01	9.14E-01
115-07-1	Propylene (Propene)	0.00E+00	7.32E-03	8.82E+00
129-00-0	Pyrene (category: PAH)	0.00E+00	1.87E-01	not searched
7440-20-2	Scandium (Sc)	1.00E+00	1.00E+00	not searched
7782-49-2	Selenium (Se)	0.00E+00	9.33E+02	4.40E+01
7440-21-3	Silicon (Si)	1.00E+00	1.00E+00	not searched
7440-22-4	Silver	0.00E+00	1.00E+04	1.01E+04
no CAS #	SAC (tin-silver-copper) alloy*	9.55E-01	3.91E+02	not searched
no CAS #	SABC (tin-silver-bismuth-copper) alloy*	9.70E-01	2.51E+02	not searched
no CAS #	SnCu (in-copper) alloy*	9.92E-01	1.20E+00	not searched
no CAS #	SnPb (tin-lead) alloy*	1.00E+00	2.31E+04	not searched
7681-52-9	Sodium Hypochlorite	0.00E+00	6.67E+00	1.24E+02
7440-24-6	Strontium (Sr)	1.00E+00	7.37E-02	3.12E-01
100-42-5	Styrene	1.00E+00	1.40E-01	1.50E+01
7446-09-5	Sulfur dioxide	0.00E+00	6.60E+02	not searched
no CAS#	Sulfur oxides (SOx)	1.00E+00	1.00E+00	not searched
7664-93-9	Sulfuric acid	1.00E+00	6.87E+02	2.74E+00

Table E-2. Toxicity hazard values (HV) for potentially toxic chemicals in the LFSP

CAS#	Material (flow)	Cancer HV	Non-cancer HV	Aquatic ecotoxicity HV
127-18-4	Tetrachloroethylene (Tetrachloroethene, Perchloroethyl	7.32E-02	1.00E+00	3.40E+00
7440-28-0	Thallium (Tl)	1.00E+00	1.00E+00	not searched
7440-31-5	Tin (Sn)	1.00E+00	1.00E+00	1.02E-01
7440-32-6	Titanium	1.00E+00	8.58E+01	2.00E+00
108-88-3	Toluene	0.00E+00	1.67E-01	1.70E+00
71-55-6	Trichloroethane (1,1,1-trichloroethane)	1.00E+00	5.68E-02	1.07E+00
67-66-3	Trichloromethane (Chloroform)	4.76E-02	1.09E+01	5.63E-01
7440-62-2	Vanadium (V)	1.00E+00	4.67E+03	1.20E+01
108-05-4	Vinyl acetate	0.00E+00	3.90E-01	4.02E-01
1330-20-7	Xylene (C24H30) [mixed isomers]	0.00E+00	7.82E-02	5.79E+00
7440-66-6	Zinc (Zn)	0.00E+00	1.56E+01	3.82E+02
No CAS #	Zinc (Zn++)	1.00E+00	1.00E+00	6.63E+00
7733-02-0	Zinc sulfate	0.00E+00	1.40E+02	8.08E+01
Key:				
CAS=Chemical Abstracts Service.				
HV=Hazard value. The methodologies for calculating the HVs are in Sections 3.2.11 through 3.2.13.				
not searched=aquatic ecotoxicity HV was not needed for the LFSP and thus toxicity data were not collected.				
*HVs for each solder alloy were calculated as a weighted average of the HV for each comoponent metal in the alloy.				

Table E-3. Materials excluded from toxic classification

CAS#	Material (flow)	Reason for exclusion
NA	BOD (Biological Oxygen Demand)	judgement
106-97-8	Butane (n-C4H10)	GRAS
7440-70-2	Calcium (Ca)	judgement
124-38-9	Carbon Dioxide (CO2)	judgement
NA	Carbonate ion [Carbonates (CO3--, HCO3-, CO2]	judgement
NA	Charcoal	judgement
NA	COD (Chemical Oxygen Demand)	judgement
16887-00-6	Chloride (Cl-)	judgement
NA	Dissolved solids	judgement
64-17-5	Ethanol (Ethyl Alcohol)	GRAS
7440-59-7	Helium (He)	GRAS
7439-89-6	Iron (Fe)	judgement
NA	Iron (Fe++, Fe3+)	judgement
8008-20-6	Kerosene	judgement
7727-37-9	Nitrogen	GRAS
74-98-6	n-Propane [Propane (C3H8)]	GRAS
NA	Phosphates (PO4-3)	judgement
79-09-4	Propionic Acid	GRAS
NA	Salts (unspecified)	judgement
NA	Sawdust	judgement
7440-23-5	Sodium (Na)	judgement
NA	Sodium (Na+)	judgement
497-19-8	Sodium carbonate (Na2CO3, soda ash)	judgement
1310-73-2	Sodium hydroxide (NaOH)	judgement
14808-79-8	Sulfates (SO4--)	judgement
18496-25-8	Sulfides (S--)	judgement
14265-45-3	Sulfites (SO3--)	judgement
7704-34-9	Sulfur	judgement
NA	Suspended Solids	judgement
NA	TOCs (Total organic compounds)	judgement

CAS#=Chemical Abstracts Service Registry Number

NA=not applicable

GRAS="Generally Regarded as Safe" according to the U.S. Food and Drug Admimistration

Table E-4. FINAL TOXICITY DATA SELECTIONS FOR USE IN THE LCIA

Cas #	Material	Selection comments by UT	oral or inhal SF	WOE (EPA & IARC)	oral NOAEL (mg/kg-day)	inhal NOAEL (mg/m3)	oral LOAEL (a) (mg/kg-day)	inhal LOAEL (a) (mg/m3)	fish LC50 (mg/L)	fish NOEL (mg/L)
For human and ecological endpoints:										
207-08-9	Benzo(k)fluoranthene	inhalation NOAEL not used as it is an occupational limit, presumably including safety and/or uncertainty factors, thus not consistent with a NOAEL; no supporting NOAEL or LOAEL found; therefore, assume "no data"	--	B2	--	--	--	--	**	0.006
16872-11-0	Fluoroboric acid	inhalation NOAEL not used as it is an occupational limit, presumably including safety and/or uncertainty factors; therefore, not consistent with a NOAEL; no supporting NOAEL or LOAEL found; therefore, assume "no data." The NOAEL is actually a dermal "NOAEL/LOAEL" as reported in the PWB CTSA (USEPA 1998a)	--	--	--	--	0.77	--	>1000	>=20
16961-83-4	Fluorosilicic acid	inhalation NOAEL not used as it is an occupational limit, presumably including safety and/or uncertainty factors; therefore, not consistent with a NOAEL; no supporting NOAEL or LOAEL found; therefore, assume "no data." The NOAEL is actually a dermal "NOAEL/LOAEL" as reported in the PWB CTSA (USEPA 1998a)	--	--	--	--	0.77	--	>100	>10
(b)	Flux A		--	--	--	--	--	--	900	90
(b)	Flux B		--	--	450	200	1000	810	930	100
(b)	Flux D	the fish LC50 is based on same chemical name, but with a different CAS# than we were provided	--	--	--	--	--	--	<=0.5	<=0.05
(b)	Flux E		--	--	--	--	--	--	>1000	>100
(b)	Flux F	since the source of the LC50 data does not supply the original data source of the toxicity value, we chose to use the ECOSAR estimate	--	--	500	--	--	--	5.4	0.87
1309-36-0	Iron pyrite	inhalation NOAEL not used as it is an occupational limit, presumably including safety and/or uncertainty factors, thus not consistent with a NOAEL; no supporting NOAEL or LOAEL found; therefore, assume "no data"	--	--	--	--	--	--	**	**
7733-02-0	Zinc sulfate	chose fathead minnow data (1.27 mg/L) instead of rainbow trout data; based on our methodology (i.e., exclude trout data due to species sensitivity) (Swanson et al. 1997)	--	D	--	--	1	--	14	0.8
7440-69-9	Bismuth	for oral NOAEL, converted 227 g/d using 70 kg body weight; didn't use inhalation NOAEL as it is a PEL (occupational limit) which incorporates time-weighted exposure and possibly safety and/or uncertainty factors and thus not consistent with a NOAEL	--	3243	--	--	--	--	5	0.5
For fish LC50 and fish NOEL endpoints only:										

Table E-4. FINAL TOXICITY DATA SELECTIONS FOR USE IN THE LCIA

Cas #	Material	Selection comments by UT	oral or inhal SF	WOE (EPA & IARC)	oral NOAEL (mg/kg-day)	inhal NOAEL (mg/m3)	oral LOAEL (a) (mg/kg-day)	inhal LOAEL (a) (mg/m3)	fish LC50 (mg/L)	fish NOEL (mg/L)
7429-90-5	Aluminum	took average of LC50s							11	3.3
7440-41-7	Beryllium								2	0.2
7782-41-4	Fluorine	took average of LC50s							>100	>10
7782-49-2	Selenium	took average of LC50s							4.9	0.1
7681-52-9	Sodium Hypochlorite	took average of LC50s							0.530 (measured)	<=0.05
7440-24-6	Strontium	took average of LC50s							210	20
7440-62-2	Vanadium	used rainbow trout listed in fish LC50 column, as fathead minnow data source had no date and did not provide time period of the test							4	0.67

Notes:
Dark shading indicates data are not needed
(a) LOAEL only needed if no NOAEL found (LOAEL/10 will be used to represent NOAEL)
(b) Flux material names and CAS#s have been withheld to protect confidentiality
-- = no data
** = low toxicity

Table E-5. HUMAN HEALTH TOXICITY DATA COLLECTION

Cas #	Material	oral SF (mg/kg-day)-1	inhal SF (mg/kg-day)-1	WOE (EPA & IARC)	Source*	oral NOAEL (mg/kg-day)	Source*	inhal NOAEL (mg/m3)	Source*	oral LOAEL (a) (mg/kg-day)	Source*	inhal LOAEL (a) (mg/m3)	Source*
Searched for human and ecological toxicity endpoints:													
207-08-9	Benzo(k)fluoranthene	N/A	N/A	**B2**	U.S. EPA, 1997	N/A		0.04 (Norway OEL, human)	RTECS, 2003b	N/A		N/A	
16872-11-0	Fluoroboric acid	N/A	N/A	N/A		N/A		2.5 as F (human, 8-10 hr/day, 5 d/wk)	U.S. CFR, 1994, NIOSH, 1997	**0.77** (for fluorides; human; 2 yr; bone, joint and G.I. effects)	U.S. EPA, 1998a	N/A	
16961-83-4	Fluorosilicic acid	N/A	N/A	N/A		N/A		2.5 as F (human, 8-10 hr/day, 5 d/wk)	U.S. CFR, 1994, NIOSH, 1997	**0.77** (for fluorides; human; 2 yr; bone, joint and G.I. effects)	U.S. EPA, 1998a	N/A	
(b)	Flux A	data withheld for confidentiality											
(b)	Flux B	data withheld for confidentiality											
(b)	Flux D	data withheld for confidentiality											
(b)	Flux E	data withheld for confidentiality											
(b)	Flux F	data withheld for confidentiality											
1309-36-0	Iron pyrite	N/A	N/A	N/A		N/A		1.0 (for iron salts, soluble as iron, human, 8 hr/day, 5 d/wk	ACGIH, 2002	N/A		N/A	
7733-02-0	Zinc sulfate	N/A	N/A	**D**	U.S. EPA 1998b	N/A		N/A		**1.0** (human; zinc cmpds. as zinc)	U.S. EPA 1998b	N/A	
7440-69-9	Bismuth	N/A	N/A	N/A		**227**g/d (human, 3 wk)	HSDB, 2003	2.5 (PEL for 8 hr day, 5 d/wk, for bismuth fluoride)	U.S. CFR, 1994	221 mg/kg (LDLo, human)	Arena, 1970	N/A	

Notes:
(a) LOAEL only needed if no NOAEL found (LOAEL/10 will be used to represent NOAEL)
Cancer WOE B2 = Probable human carcinogen
Cancer WOE D = Not classifiable as to human carcinogenicity
* Full citations of sources are provided in the References section of this Appendix (E.3)
(b) Flux material names and CAS#s have been withheld to protect confidentiality
BOLD indicates values used for LFSP

Table E-6. AQUATIC TOXICITY DATA COLLECTION

Cas #	Material	fish LC50 (mg/L)	Source*	fish NOEL (mg/L)	Source*	ECOSAR LC50 mg/L (predicted 96-hr)	ECOSAR Chronic mg/L (predicted)	Source*
207-08-9	Benzo(k)fluoranthene	**0.026** (96 hr predicted value for fish exceeds water solubility)	U.S.EPA, 2003a	NA		**	**0.006**	U.S.EPA, 2003b
16872-11-0	Fluoroboric acid	NA		N/A		**>1000**	**>=20**	U.S.EPA, 2003b
16961-83-4	Fluorosilicic acid	49 (as sodium fluorosilicate, bluegill, 96 hr)	Dawson et al., 1977	N/A		**>100**	**>10**	U.S.EPA, 2003b
(a)	Flux A	data withheld for confidentiality						
(a)	Flux B	data withheld for confidentiality						
(a)	Flux D	data withheld for confidentiality						
(a)	Flux E	data withheld for confidentiality						
(a)	Flux F	data withheld for confidentiality						
1309-36-0	Iron pyrite	6746.128 (96 hr predicted LC50); report as **>1000**	U.S. EPA, 2002	N/A		**	**	U.S.EPA, 2003b
7733-02-0	Zinc sulfate	1.27 (fathead minnow, 96 hr LC50)	Erten-Unal, et al., 1998	N/A		**14.0**	**0.800**	U.S.EPA, 2003b
7440-69-9	Bismuth	N/A		N/A		**5.0**	**0.500**	U.S.EPA, 2003b
7429-90-5	Aluminum	0.12,0.16,0.31 (rainbow trout; static, 96 hr)	Holtze, 1983	N/A		**11.0**	**3.3**	U.S.EPA, 2003b
7440-41-7	Beryllium	37.9 (fathead minnow; time not given)	Cardwell et al., 1976	N/A		**2.0**	**0.200**	U.S.EPA, 2003b
7782-41-4	Fluorine	51, 128, 140, 193, 107.5, 200 (as sodium fluoride, rainbow trout, 96 hr static)	Pimentel & Bulkley, 1983; Smith et al., 1985, Camargo and Tarazona, 1991	N/A		**>100**	**>10**	U.S.EPA, 2003b
7782-49-2	Selenium	11.5, 12.5, 45, 48 (rainbow trout, 96 hr)	Goettl et al., 1976; Spehar 1986	N/A		**4.9**	**0.100**	U.S.EPA, 2003b
7681-52-9	Sodium Hypochlorite	0.08,5.9,1.56,0.44,1.37,0.39,0.58,0.18,0.17,0.79,0.14,0.72,0.35,10(fathead minnow, 96 hr)	Ewell, et al., 1986; Wilde, et al., 1983a, Wilde, et al., 1983b, Curtis et al., 1979	N/A		**0.530 (measured)**	**<=0.05**	U.S.EPA, 2003b
7440-24-6	Strontium	>0.17-<15.61(rainbow trout, 28 day)	Birge et al., 1979	N/A		**210**	**20.0**	U.S.EPA, 2003b
7440-62-2	Vanadium	0.16 (rainbow trout, 28 day)	Birge et al., 1979	N/A		**4.0**	**0.670**	U.S.EPA, 2003b

Notes:
(a) Flux material names and CAS#s have been withheld to protect confidentiality
* Full citations of sources are provided in the References section of this Appendix (E.3)
ECOSAR data in last columns were done by EPA after ORNL's search
where >/<, used absolute values
** = low toxicity
BOLD indicates values used for LFSP

Table E-7. OTHER TOXICITY-RELATED DATA

Cas #	Material	Other Mammalian Toxicity value	Source*	Other Aquatic Toxicity Value (mg/L)	Source*	Other Cancer Data	Source*
For human and ecological endpoints:							
207-08-9	Benzo(k)fluoranthene	0.0002 mg/L (MCL established for PAH's)	U.S.CFR, 2002	0.001 (13 hr LT50, Daphnia magna)	U.S. EPA, 2002	0.01 (PEF; potency equivalency factor)	U.S.EPA, 1993
16872-11-0	Fluoroboric acid			0.125 mg/L (aquatic concentration of concern, CC)	U.S. EPA 1998a		
16961-83-4	Fluorosilicic acid	430 mg/kg (oral LD50, rat)	RTECS 2003c	N/A			
(a)	Flux A	data withheld for confidentiality					
(a)	Flux B	data withheld for confidentiality					
(a)	Flux D	data withheld for confidentiality					
(a)	Flux E	data withheld for confidentiality					
(a)	Flux F	data withheld for confidentiality					
1309-36-0	Iron pyrite	49.7 mg/m3 (rabbits exhib. damaged tracheal epithelium after 0.5-8 hours inhalation exposure)	Konradova and Bencko, 1975	N/A			
7733-02-0	Zinc sulfate	14.29 mg/kg (oral TDLo for zinc & compounds, human)	RTECS 2003a	4.6 ppm (rainbow trout, 96 hr)	U.S. Coast Guard, 1984-85	3.625 mg/kg (5 day, subcutan; equivocal tumorigenic agent, rabbit)	RTECS 2003a
7440-69-9	Bismuth	0.05 mg/L (0.0014 mg/kg/day in drinking water for 70 kg human)	Ku & Schoenung, 2002	N/A			
For fish LC50 and fish NOEL endpoints only:							
7429-90-5	Aluminum			N/A			
7440-41-7	Beryllium			N/A			
7782-41-4	Fluorine			2.3 ppm (TLm for trout, time not specified)	Weiss 1980		
7782-49-2	Selenium						
7681-52-9	Sodium Hypochlorite			<1.7 mg/L (fish acute toxicity value; <0.02 mg/L CC	U.S. EPA, 1996		
7440-24-6	Strontium			N/A			
7440-62-2	Vanadium			1.8-1.9 (LC50, fathead minnow)	Kimball, n.d.		

Note:
Dark shading indicates data are not needed
* Full citations of sources are provided in the References section of this Appendix (E.3)
(a) Flux material names and CAS#s have been withheld to protect confidentiality

Table E-8. Chemicals used to calculate geometric mean slope factor values for carcinogenic hazard value

Chemical	CAS #	Oral Slope Factor (mg/kg-day)-1	Inhalation Slope Factor (mg/kg-day)-1
Acephate	30560-19-1	8.70E-03	
Acetaldehyde	75-07-0		7.70E-03
Acrylamide	79-06-1	4.50E+00	4.50E+00
Acrylonitrile	107-13-1	5.40E-01	2.40E-01
Alachlor	15972-60-8	8.00E-02	
Aldrin	309-00-2	1.70E+01	1.70E+01
Aniline	62-53-3	5.70E-03	
Aramite	140-57-8	2.50E-02	2.50E-02
Aroclor 1016	12674-11-2	4.00E-01	4.00E-01
Aroclor 1016	12674-11-2	2.00E+00	2.00E+00
Aroclor 1221	11104-28-2	4.00E-01	4.00E-01
Aroclor 1221	11104-28-2	2.00E+00	2.00E+00
Aroclor 1232	11141-16-5	4.00E-01	4.00E-01
Aroclor 1232	11141-16-5	2.00E+00	2.00E+00
Aroclor 1242	53469-21-9	4.00E-01	4.00E-01
Aroclor 1242	53469-21-9	2.00E+00	2.00E+00
Aroclor 1248	12672-29-6	4.00E-01	4.00E-01
Aroclor 1248	12672-29-6	2.00E+00	2.00E+00
Aroclor 1254	11097-69-1	4.00E-01	4.00E-01
Aroclor 1254	11097-69-1		2.00E+00
Aroclor 1260	11096-82-5	4.00E-01	4.00E-01
Aroclor 1260	11096-82-5	2.00E+00	2.00E+00
Arsenic, Inorganic	7440-38-2	1.50E+00	5.00E+01
Atrazine	1912-24-9	2.22E-01	
Azobenzene	103-33-3	1.10E-01	1.10E-01
Benz[a]anthracene	56-55-3	7.30E-01	3.10E-01
Benzene	71-43-2	5.50E-02	2.90E-02
Benzidine	92-87-5	2.30E+02	2.30E+02
Benzo[a]pyrene	50-32-8	7.30E+00	3.10E+00
Benzo[b]fluoranthene	205-99-2	7.30E-01	3.10E-01
Benzo[k]fluoranthene	207-08-9	7.30E-02	3.10E-02
Benzotrichloride	98-07-7	1.30E+01	
Benzyl Chloride	100-44-7	1.70E-01	
Beryllium and compounds	7440-41-7	4.30E+00	8.40E+00
Bis(2-chloro-1-methylethyl)ether (Technical)	108-60-1	7.00E-02	3.50E-02
Bis(2-chloroethyl)ether	111-44-4	1.10E+00	1.10E+00
Bis(2-ethylhexyl)phthalate	117-81-7	1.40E-02	
Bis(chloromethyl)ether	542-88-1	2.20E+02	2.20E+02
Bromodichloromethane	75-27-4	6.20E-02	
Bromoform	75-25-2	7.90E-03	3.90E-03
Butadiene, 1,3-	106-99-0		1.80E+00
Cadmium (Diet)	7440-43-9		6.10E+00
Cadmium (Water)	7440-43-9		6.10E+00
Captafol	2425-06-1	8.60E-03	
Captan	133-06-2	3.50E-03	
Carbazole	86-74-8	2.00E-02	
Carbon Tetrachloride	56-23-5	1.30E-01	5.30E-02
Chloranil	118-75-2	4.03E-01	
Chlordane	057-74-9	3.50E-01	1.30E+00
Chloro-2-methylaniline HCl, 4-	3165-93-3	4.60E-01	
Chloro-2-methylaniline, 4-	95-69-2	5.80E-01	

Table E-8. Chemicals used to calculate geometric mean slope factor values for carcinogenic hazard value

Chemical	CAS #	Oral Slope Factor (mg/kg-day)-1	Inhalation Slope Factor (mg/kg-day)-1
Chlorobenzilate	510-15-6	2.70E-01	2.70E-01
Chlorodibromoethane	73506-94-2	8.40E-02	
Chloroform	67-66-3	6.10E-03	8.10E-02
Chloromethane	74-87-3	1.30E-02	6.30E-03
Chloronitrobenzene, o-	88-73-3	2.50E-02	
Chloronitrobenzene, p-	121-73-3	1.80E-02	
Chlorothalonil	1897-45-6	1.10E-02	
Chromium VI (chromic acid mists)	18540-29-9		4.10E+01
Chromium VI (particulates)	18540-29-9		4.10E+01
Chrysene	218-01-9	7.30E-03	3.10E-03
Coke Oven Emissions	8007-45-2		2.20E+00
Crotonaldehyde, trans-	123-73-9	1.90E+00	
Cyanazine	21725-46-2	8.40E-01	
Cyclohexane, 1,2,3,4,5-pentabromo-6-chloro-	87-84-3	2.30E-02	
DDD	72-54-8	2.40E-01	
DDE	72-55-9	3.40E-01	
DDT	50-29-3	3.40E-01	3.40E-01
Di(2-ethylhexyl)adipate	103-23-1	1.20E-03	
Diallate	2303-16-4	6.10E-02	
Dibenz[a,h]anthracene	53-70-3	7.30E+00	3.10E+00
Dibromo-3-chloropropane, 1,2-	96-12-8	1.40E+00	2.40E-03
Dibromochloromethane	124-48-1	8.40E-02	
Dibromoethane, 1,2-	106-93-4	8.50E+01	7.60E-01
Dichloro-2-butene, 1,4-	764-41-0		9.30E+00
Dichlorobenzene, 1,4-	106-46-7	2.40E-02	
Dichlorobenzidine, 3,3'-	91-94-1	4.50E-01	
Dichloroethane, 1,2-	107-06-2	9.10E-02	9.10E-02
Dichloroethylene, 1,1-	75-35-4	6.00E-01	1.20E+00
Dichloropropane, 1,2-	78-87-5	6.80E-02	
Dichloropropene, 1,3-	542-75-6	1.00E-01	1.40E-02
Dichlorvos	62-73-7	2.90E-01	
Dieldrin	60-57-1	1.60E+01	1.60E+01
Diethylstilbesterol	56-53-1	4.70E+03	4.90E+02
Dimethoxybenzidine, 3,3'-	119-90-4	1.40E-02	
Dimethylaniline HCl, 2,4-	21436-96-4	5.80E-01	
Dimethylaniline, 2,4-	095-68-1	7.50E-01	
Dimethylbenzidine, 3,3'-	119-93-7	9.20E+00	
Dimethylhydrazine, 1,1-	57-14-7	3.00E+00	1.72E+01
Dinitrotoluene Mixture, 2,4/2,6-	25321-14-6	6.80E-01	
Dinitrotoluene, 2,4-	121-14-2	6.80E-01	
Dinitrotoluene, 2,6-	606-20-2	6.80E-01	
Dioxane, 1,4-	123-91-1	1.10E-02	
Diphenylhydrazine, 1,2-	122-66-7	8.00E-01	8.00E-01
Direct Black 38	1937-37-7	8.60E+00	
Direct Blue 6	2602-46-2	8.10E+00	
Direct Brown 95	16071-86-6	9.30E+00	
Epichlorohydrin	106-89-8	9.90E-03	4.20E-03
Ethyl Acrylate	140-88-5	4.80E-02	
Ethylbenzene	100-41-4		3.85E-03
Ethylene Oxide	75-21-8	1.02E+00	3.50E-01
Ethylene Thiourea	96-45-7	1.10E-01	

Table E-8. Chemicals used to calculate geometric mean slope factor values for carcinogenic hazard value

Chemical	CAS #	Oral Slope Factor (mg/kg-day)-1	Inhalation Slope Factor (mg/kg-day)-1
Folpet	133-07-3	3.50E-03	
Fomesafen	72178-02-0	1.90E-01	
Formaldehyde	50-00-0		4.50E-02
Furazolidone	67-45-8	3.80E+00	
Furium	531-82-8	5.00E+01	
Furmecyclox	60568-05-0	3.00E-02	
Heptachlor	76-44-8	4.50E+00	4.50E+00
Heptachlor Epoxide	1024-57-3	9.10E+00	9.10E+00
Hexachlorobenzene	118-74-1	1.60E+00	1.60E+00
Hexachlorobutadiene	87-68-3	7.80E-02	7.80E-02
Hexachlorocyclohexane, Alpha-	319-84-6	6.30E+00	6.30E+00
Hexachlorocyclohexane, Beta-	319-85-7	1.80E+00	1.80E+00
Hexachlorocyclohexane, Gamma-	58-89-9	1.30E+00	
Hexachlorocyclohexane, Technical	608-73-1	1.80E+00	1.80E+00
Hexachlorodibenzo-p-dioxin, Mixture	19408-74-3	6.20E+03	4.55E+03
Hexachloroethane	67-72-1	1.40E-02	1.40E-02
Hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX)	121-82-4	1.10E-01	
HpCDD, 2,3,7,8-	37871-00-4	1.50E+03	1.50E+03
HpCDF, 2,3,7,8-	38998-75-3	1.50E+03	1.50E+03
HxCDD, 2,3,7,8-	34465-46-8	1.50E+04	1.50E+04
HxCDF, 2,3,7,8-	55684-94-1	1.50E+04	1.50E+04
Hydrazine	302-01-2	3.00E+00	1.70E+01
Hydrazine Sulfate	10034-93-2	3.00E+00	1.70E+01
Indeno[1,2,3-cd]pyrene	193-39-5	7.30E-01	3.10E-01
Isophorone	78-59-1	9.50E-04	
Methoxy-5-nitroaniline, 2-	99-59-2	4.60E-02	
Methyl Hydrazine	60-34-4	3.00E+00	1.72E+01
Methyl-5-Nitroaniline, 2-	99-55-8	3.30E-02	
Methylaniline Hydrochloride, 2-	636-21-5	1.80E-01	
Methylene Chloride	75-09-2	7.50E-03	1.65E-03
Methylene-bis(2-chloroaniline), 4,4'-	101-14-4	1.30E-01	1.30E-01
Methylene-bis(N,N-dimethyl) Aniline, 4,4'-	101-61-1	4.60E-02	
Methylenebisbenzenamine, 4,4'-	101-77-9	2.50E-01	
Mirex	2385-85-5	1.80E+00	
Nickel Refinery Dust	NA		8.40E-01
Nickel Subsulfide	12035-72-2		1.70E+00
Nitrofurazone	59-87-0	1.50E+00	
Nitropropane, 2-	79-46-9	9.50E+00	9.40E+00
Nitrosodiethanolamine, N-	1116-54-7	2.80E+00	
Nitrosodiethylamine, N-	55-18-5	1.50E+02	1.50E+02
Nitrosodimethylamine, N-	62-75-9	5.10E+01	5.10E+01
Nitroso-di-N-butylamine, N-	924-16-3	5.40E+00	5.40E+00
Nitroso-di-N-propylamine, N-	621-64-7	7.00E+00	
Nitrosodiphenylamine, N-	86-30-6	4.90E-03	
Nitrosomethylethylamine, N-	10595-95-6	2.20E+01	
Nitroso-N-ethylurea, N-	759-73-9	1.40E+02	
Nitrosopyrrolidine, N-	930-55-2	2.10E+00	2.10E+00
OCDD	3268-87-9	1.50E+02	1.50E+02
OCDF	39001-02-0	1.50E+02	1.50E+02
PeCDD, 2,3,7,8-	36088-22-9	7.50E+04	7.50E+04
PeCDF, 1,2,3,7,8-	57117-41-6	7.50E+04	7.50E+04

Table E-8. Chemicals used to calculate geometric mean slope factor values for carcinogenic hazard value

Chemical	CAS #	Oral Slope Factor (mg/kg-day)-1	Inhalation Slope Factor (mg/kg-day)-1
PeCDF, 2,3,4,7,8-	57117-31-4	7.50E+03	7.50E+03
Pentachloronitrobenzene	82-68-8	2.60E-01	
Pentachlorophenol	87-86-5	1.20E-01	
Phenylenediamine, o-	95-54-5	4.70E-02	
Phenylphenol, 2-	90-43-7	1.94E-03	
Polybrominated Biphenyls	59536-65-1	8.90E+00	
Polychlorinated Biphenyls (high risk)	1336-36-3	2.00E+00	2.00E+00
Polychlorinated Biphenyls (low risk)	1336-36-3	4.00E-01	4.00E-01
Polychlorinated Biphenyls (lowest risk)	1336-36-3	7.00E-02	
Prochloraz	67747-09-5	1.50E-01	
Propylene Oxide	75-56-9	2.40E-01	1.30E-02
Quinoline	91-22-5	1.20E+01	
Simazine	122-34-9	1.20E-01	
Sodium Diethyldithiocarbamate	148-18-5	2.70E-01	
Stirofos (Tetrachlorovinphos)	961-11-5	2.40E-02	
TCDD, 2,3,7,8-	1746-01-6	1.50E+05	1.50E+05
TCDF, 2,3,7,8-	51207-31-9	1.50E+04	1.50E+04
Tetrachloroethane, 1,1,1,2-	630-20-6	2.60E-02	2.60E-02
Tetrachloroethane, 1,1,2,2-	79-34-5	2.00E-01	2.00E-01
Tetrachloroethylene	127-18-4	5.20E-02	2.00E-03
Tetrachlorotoluene, p- alpha, alpha, alpha-	5216-25-1	2.00E+01	
Toluene-2,4-diamine	95-80-7	3.20E+00	
Toluidine, o- (Methylaniline, 2-)	95-53-4	2.40E-01	
Toluidine, p-	106-49-0	1.90E-01	
Toxaphene	8001-35-2	1.10E+00	1.10E+00
Trichloroaniline HCl, 2,4,6-	33663-50-2	2.90E-02	
Trichloroaniline, 2,4,6-	634-93-5	3.40E-02	
Trichloroethane, 1,1,2-	79-00-5	5.70E-02	5.70E-02
Trichloroethylene	79-01-6	1.10E-02	6.00E-03
Trichlorophenol, 2,4,6-	88-06-2	1.10E-02	1.00E-02
Trichloropropane, 1,2,3-	96-18-4	7.00E+00	
Trifluralin	1582-09-8	7.70E-03	
Trimethyl Phosphate	512-56-1	3.70E-02	
Trinitrotoluene, 2,4,6-	118-96-7	3.00E-02	
Vinyl Bromide	593-60-2		1.10E-01
Vinyl Chloride	75-01-4	1.40E+00	3.08E-02
geometric mean		**0.71**	**1.70**
count (n)		**175**	**105**
min		**0.00095**	**0.00165**
max		**150000**	**150000**

blank=no data

Source: Risk Assessment Information System (RAIS), http://risk.lsd.ornl.gov/cgi-bin/tox/TOX_9801 (downloaded 11/00): IRIS/HEAST Slope Factors.

Table E-9. Oral No Observable Adverse Effect Level (NOAEL) data

Chemical	CAS #	Value	unit
2,3,7,8-TCDD	1746-01-6	9E-08	Mg/KgDay
Arsenic	7440-38-2	0.0008	Mg/KgDay
Terbufos	13071-79-9	0.0025	Mg/KgDay
Vanadium	7440-62-2	0.003	Mg/KgDay
Cadmium cmpds	20-04-2	0.005	Mg/KgDay
Manganese oxide	1313-13-9	0.005	Mg/KgDay
Polychlorinated biphenyls	1336-36-3	0.007	Mg/KgDay
Phosphorus (yellow or white)	7723-14-0	0.015	Mg/KgDay
Selenium	7782-49-2	0.015	Mg/KgDay
Phosphine	7803-51-2	0.026	Mg/KgDay
Chloropyrifos	2921-88-2	0.03	Mg/KgDay
Ammonium bifluoride	1341-49-7	0.05	Mg/KgDay
Fluorine	7782-41-4	0.06	Mg/KgDay
Acrylamide	79-06-1	0.1	Mg/KgDay
1,3-Dichloropropene	542-75-6	0.125	Mg/KgDay
Manganese	7439-96-5	0.14	Mg/KgDay
2,4-Dinitrotoluene	121-14-2	0.2	Mg/KgDay
Hexachloro-1,3-butadiene	87-68-3	0.2	Mg/KgDay
Uranium	7440-61-6	0.2	Mg/KgDay
Barium	7440-39-3	0.21	Mg/KgDay
Barium carbonate	513-77-9	0.21	Mg/KgDay
Barium cmpds	20-02-0	0.21	Mg/KgDay
Barium sulfate	7727-43-7	0.21	Mg/KgDay
Bromomethane	74-83-9	0.4	Mg/KgDay
Nitrobenzene	98-95-3	0.46	Mg/KgDay
Hexachlorobenzene	118-74-1	0.5	Mg/KgDay
Copper	7440-50-8	0.53	Mg/KgDay
Lead	7439-92-1	0.57	Mg/KgDay
Cyanazine	21725-46-2	0.625	Mg/KgDay
Trifluralin	1582-09-8	0.75	Mg/KgDay
Zinc (elemental)	7440-66-6	0.9	Mg/KgDay
Acrylonitrile	107-13-1	1	Mg/KgDay
Alachlor	15972-60-8	1	Mg/KgDay
Benzene	71-43-2	1	Mg/KgDay
Carbon tetrachloride	56-23-5	1	Mg/KgDay
Decabromodiphenyl oxide	1163-19-5	1	Mg/KgDay
Hexachloroethane	67-72-1	1	Mg/KgDay
Nitrites	14797-65-0	1	Mg/KgDay
Pyridine	110-86-1	1	Mg/KgDay
Chlorothalonil	1897-45-6	1.5	Mg/KgDay
Nitrate		1.6	Mg/KgDay
Nitrates/nitrites	14797-55-8	1.6	Mg/KgDay
Sodium hypochlorite	7681-52-9	2.1	Mg/KgDay
Chromium (VI)	18540-29-9	2.5	Mg/KgDay
Ethyl dipropylthiocarbamate	759-94-4	2.5	Mg/KgDay
Methyl parathion	298-00-0	2.5	Mg/KgDay
Pentachlorophenol	87-86-5	3	Mg/KgDay
Hydrogen sulfide	7783-06-4	3.1	Mg/KgDay

Table E-9. Oral No Observable Adverse Effect Level (NOAEL) data

Chemical	CAS #	Value	unit
4,4'-Methylenedianiline	101-77-9	3.2	Mg/KgDay
Atrazine	1912-24-9	3.5	Mg/KgDay
1,1,2-Trichloroethane	79-00-5	3.9	Mg/KgDay
Butylate	2008-41-5	5	Mg/KgDay
Hydroquinone	123-31-9	5	Mg/KgDay
Nickel	7440-02-0	5	Mg/KgDay
Nickel chloride	7718-54-9	5	Mg/KgDay
Methyl methacrylate	80-62-6	7.5	Mg/KgDay
1,2,4-Trichlorobenzene	120-82-1	7.8	Mg/KgDay
Boron	7440-42-8	8.8	Mg/KgDay
Carbaryl	63-25-2	9.6	Mg/KgDay
1.4-Dichlorobenzene	106-46-7	10	Mg/KgDay
Maleic anhydride	108-31-6	10	Mg/KgDay
Cyanide (-1)	57-12-5	10.8	Mg/KgDay
Hydrogen cyanide	74-90-8	10.8	Mg/KgDay
Captan	133-06-2	12.5	Mg/KgDay
Chlorobenzene	108-90-7	12.5	Mg/KgDay
Chlorine	7782-50-5	14	Mg/KgDay
Tetrachloroethylene	127-18-4	14	Mg/KgDay
2,4-D	94-75-7	15	Mg/KgDay
Dichlorodifluoromethane	75-71-8	15	Mg/KgDay
Formaldehyde	50-00-0	15	Mg/KgDay
Bromoform	75-25-2	17.9	Mg/KgDay
1,2-Dichloroethane	107-06-2	18	Mg/KgDay
1,2-Dichlorobenzene	95-50-1	18.8	Mg/KgDay
Aluminum hydroxide	21645-51-2	23	Mg/KgDay
Trichloroethylene	79-01-6	24	Mg/KgDay
Maneb	12427-38-2	25	Mg/KgDay
Ethylene oxide	75-21-8	30	Mg/KgDay
N,N-dimethylaniline	121-69-7	32	Mg/KgDay
Ammonia	7664-41-7	34	Mg/KgDay
2-methoxyethanol	109-86-4	50	Mg/KgDay
Acetonitrile	75-05-8	50	Mg/KgDay
Biphenyl	92-52-4	50	Mg/KgDay
Chlorophenols [o]	20-05-3	50	Mg/KgDay
Di (2-ethylhexyl) phthalate	117-81-7	50	Mg/KgDay
Methyl isobutyl ketone	108-10-1	50	Mg/KgDay
P-cresol	106-44-5	50	Mg/KgDay
Aluminum (elemental)	7429-90-5	60	Mg/KgDay
Phenol	108-95-2	60	Mg/KgDay
Boric acid	11113-50-1	67	Mg/KgDay
Orthoboric acid	10043-35-3	67	Mg/KgDay
4-Nitrophenol	100-02-7	70	Mg/KgDay
Coolant	not available	71	Mg/KgDay
Ethylene glycol	107-21-1	71	Mg/KgDay
Naphthalene	91-20-3	71	Mg/KgDay
Butyraldehyde	123-72-8	75	Mg/KgDay
Diethanolamine	111-42-2	75	Mg/KgDay

Table E-9. Oral No Observable Adverse Effect Level (NOAEL) data

Chemical	CAS #	Value	unit
Pyrene	129-00-0	75	Mg/KgDay
Acrylic acid	79-10-7	83	Mg/KgDay
Butyl acrylate	141-32-2	84	Mg/KgDay
Acetone	67-64-1	100	Mg/KgDay
Methyl tert-butyl ether	1634-04-4	100	Mg/KgDay
Nickel cmpds	20-14-4	100	Mg/KgDay
Styrene	100-42-5	100	Mg/KgDay
Toluene	108-88-3	100	Mg/KgDay
Vinyl acetate	108-05-4	100	Mg/KgDay
Acetaldehyde	75-07-0	125	Mg/KgDay
Dibutyl phthalate	84-74-2	125	Mg/KgDay
Fluoranthene	206-44-0	125	Mg/KgDay
Fluorene	86-73-7	125	Mg/KgDay
Methyl ethyl ketone	78-93-3	125	Mg/KgDay
N-butyl alcohol	71-36-3	125	Mg/KgDay
Ethylbenzene	100-41-4	136	Mg/KgDay
Benzaldehyde	100-52-7	143	Mg/KgDay
Diethyl phthalate	84-66-2	150	Mg/KgDay
Isophorone	78-59-1	150	Mg/KgDay
Butyl benzyl phthalate	85-68-7	151	Mg/KgDay
Cumene	98-82-8	154	Mg/KgDay
Dichloromethane	75-09-2	155	Mg/KgDay
Acenaphthene	83-32-9	175	Mg/KgDay
m, p-xylene	1330-20-7	179	Mg/KgDay
o-xylene	95-47-6	179	Mg/KgDay
Xylene (mixed isomers)	1330-20-7	179	Mg/KgDay
Strontium	7440-24-6	190	Mg/KgDay
Strontium carbonate	1633-05-2	190	Mg/KgDay
Acetic acid	64-19-7	195	Mg/KgDay
Dioctyl sebacate	122-62-3	200	Mg/KgDay
Propylene oxide	75-56-9	200	Mg/KgDay
Glycol ethers	111-76-2	203	Mg/KgDay
Isopropyl alcohol	67-63-0	230	Mg/KgDay
1,1,1-Trichloroethane	71-55-6	250	Mg/KgDay
1,2-Dichloropropane	78-87-5	250	Mg/KgDay
2-ethoxyethanol	110-80-5	250	Mg/KgDay
m-xylene	108-38-3	250	Mg/KgDay
1,2-Dichlorotetrafluoroethane	76-14-2	273	Mg/KgDay
Freon 113	76-13-1	273	Mg/KgDay
Metolachlor	51218-45-2	300	Mg/KgDay
Ethanol amine	141-43-5	320	Mg/KgDay
Acetophenone	98-86-2	423	Mg/KgDay
Di propylene glycol butyl ether	29911-28-2	450	Mg/KgDay
4,4'-Isopropylidenediphenol	80-05-7	500	Mg/KgDay
Diethyl ether	60-29-7	500	Mg/KgDay
Methanol	67-56-1	500	Mg/KgDay
Terephthalic acid	100-21-0	500	Mg/KgDay
Polyvinyl pyrrolidone (PVP)	9003-39-8	550	Mg/KgDay

Table E-9. Oral No Observable Adverse Effect Level (NOAEL) data

Chemical	CAS #	Value	unit
Bis (2-ethylhexyl) adipate	103-23-1	610	Mg/KgDay
Tetrahydrofuran	109-99-9	782	Mg/KgDay
Glyphosate	1071-83-6	800	Mg/KgDay
2-(2-butoxyethoxy)-ethanol acetate	124-17-4	1000	Mg/KgDay
Anthracene	120-12-7	1000	Mg/KgDay
Dimethyl phthalate	131-11-3	1000	Mg/KgDay
Heptane	142-82-5	1000	Mg/KgDay
p-xylene	106-42-3	1000	Mg/KgDay
Phosphate ester	57583-54-7	1000	Mg/KgDay
Polyethylene mono (nonylphenyl) ether glycol	9016-45-9	1000	Mg/KgDay
Diethylene glycol	111-46-6	1250	Mg/KgDay
Chromium (III)	16065-83-1	1468	Mg/KgDay
Chromium trioxide	1333-82-0	1468	Mg/KgDay
Tert-butyl alcohol	75-65-0	1599	Mg/KgDay
Bismuth	7440-69-9	3243	Mg/KgDay
Zirconium	7440-67-7	3494	Mg/KgDay
	Count n=	160	
	geometric mean=	13.987	
	minumum=	9E-08	
	maximum=	3494	

Table E-10. Inhalation No Observable Adverse Effect Level (NOAEL)

Chemical	CAS #	Value	unit
1,1,1-Trichloroethane	71-55-6	1214.9	mg/m3
1,2,4-Trichlorobenzene	120-82-1	24.3	mg/m3
1,2-Dichloroethane	107-06-2	221	mg/m3
1,2-Dichloropropane	78-87-5	710	mg/m3
1,3-Butadiene	106-99-0	2800	mg/m3
1,3-Dichloropropene	542-75-6	49.6	mg/m3
1,4-Dichlorobenzene	106-46-7	75	mg/m3
1,4-Dioxane	123-91-1	360	mg/m3
1-Methoxy-2-propanol	107-98-2	658	mg/m3
2-Ethoxyethanol	110-80-5	7480	mg/m3
2-Methoxyethanol	109-86-4	93.3	mg/m3
4,4'-Isopropylidenediphenol	80-05-7	10	mg/m3
4-Nitrophenol	100-02-7	30	mg/m3
Acetaldehyde	75-07-0	300	mg/m3
Acetonitrile	75-05-8	91.5	mg/m3
Acrylic acid	79-10-7	74	mg/m3
Allyl chloride	107-05-1	68.3	mg/m3
Ammonia	7664-41-7	40	mg/m3
Ammonium nitrate (solution)	6484-52-2	185	mg/m3
Aniline	62-53-3	19	mg/m3
Benzene	71-43-2	1.15	mg/m3
Bromomethane	74-83-9	4.3	mg/m3
Butyl acrylate	141-32-2	120	mg/m3
Butyl benzyl phthalate	85-68-7	144	mg/m3
Butyraldehyde	123-72-8	3200	mg/m3
Carbon disulfide	75-15-0	10	mg/m3
Carbon monoxide	630-08-0	114.5	mg/m3
Carbon tetrachloride	56-23-5	34.3	mg/m3
Chlorobenzene	108-90-7	377	mg/m3
Coolant	not available	10	mg/m3
Cumene	98-82-8	537	mg/m3
Cumene hydroperoxide	80-15-9	31	mg/m3
Cyclohexane	110-82-7	1500	mg/m3
Di (2-ethylhexyl) phthalate	117-81-7	50	mg/m3
Dichlorobenzene (mixed isomers)	25321-22-6	610.4	mg/m3
Dichloromethane	75-09-2	796	mg/m3
Diethanolamine	111-42-2	0.27	mg/m3
Epichlorohydrin	106-89-8	20.7	mg/m3
Ethyl chloride	75-00-3	3600	mg/m3
Ethylbenzene	100-41-4	2370	mg/m3
Ethylene	74-85-1	11600	mg/m3
Ethylene glycol	107-21-1	10	mg/m3
Ethylene oxide	75-21-8	18	mg/m3
Formaldehyde	50-00-0	0.6	mg/m3
Glycol ethers	111-76-2	121	mg/m3
HCFC-22	75-45-6	5260	mg/m3
Hexachloro-1,3-butadiene	87-68-3	58.2	mg/m3
HFC-125	354-33-6	245000	mg/m3
Hydrochloric acid	7647-01-0	15	mg/m3
Isopropyl alcohol	67-63-0	268.3	mg/m3
Maneb	12427-38-2	10	mg/m3

Table E-10. Inhalation No Observable Adverse Effect Level (NOAEL)

Chemical	CAS #	Value	unit
Mercury	7439-97-6	0.006	mg/m3
Methanol	67-56-1	130	mg/m3
Methyl chloride	74-87-3	1138.4	mg/m3
Methyl ethyl ketone	78-93-3	8047	mg/m3
Methyl isobutyl ketone	108-10-1	224	mg/m3
Methyl methacrylate	80-62-6	111.7	mg/m3
Metyl tert-butyl ether	1634-04-4	2880	mg/m3
N,N-Dimethylaniline	121-69-7	0.006	mg/m3
N-butyl alcohol	71-36-3	0.1	mg/m3
Nitrobenzene	98-95-3	27.5	mg/m3
p-cresol	106-44-5	10	mg/m3
p-xylene	106-42-3	5812.6	mg/m3
Phosphine	7803-51-2	0.25	mg/m3
Phosphoric acid	7664-38-2	50	mg/m3
Propionaldehyde	123-38-6	200	mg/m3
Propylene	115-07-1	9375	mg/m3
Propylene glycol	57-55-6	170	mg/m3
Propylene oxide	75-56-9	237	mg/m3
Sec-butyl alcohol	78-92-2	8270	mg/m3
Styrene	100-42-5	565	mg/m3
Sulfur dioxide	7446-09-5	0.104	mg/m3
Sulfuric acid	7664-93-9	0.1	mg/m3
Terephthalic acid	100-21-0	3	mg/m3
Tetrachloroethylene	127-18-4	740.2	mg/m3
Tetrahydrofuran	109-99-9	0.2	mg/m3
Titanium	7440-32-6	0.8	mg/m3
Titanium tetrachloride	7550-45-0	0.009	mg/m3
Toluene	108-88-3	411.1	mg/m3
Toluene-2,4-diisocyanate	584-84-9	0.03	mg/m3
Trichloroethylene	79-01-6	586.6	mg/m3
Vinyl acetate	108-05-4	176	mg/m3
Vinyl chloride	75-01-4	69754.5	mg/m3
Vinylidene chloride	75-35-4	120	mg/m3
	Count n=	84	
	Geometric mean=	68.6653	
	minimum=	0.006	
	maximum=	245000	

Table E-11. Fish Lethal Concentration to 50 percent of exposed population (LC_{50})

Chemical	CAS #	Value	unit
1,1,1-Trichloroethane	71-55-6	48	mg/L
1,1,2-Trichloroethane	79-00-5	82	mg/L
1,2,3,5-Tetrachlorobenzene	634-90-2	4	mg/L
1,2,4-Trichlorobenzene	120-82-1	3	mg/L
1,2,4-Trimethylbenzene	95-63-6	8	mg/L
1,2-Dichlorobenzene	95-50-1	1	mg/L
1,2-Dichloroethane	107-06-2	136	mg/L
1,2-Dichloropropane	78-87-5	127	mg/L
1,3-Butadiene	106-99-0	4	mg/L
1,3-Dichloropropene	542-75-6	0.24	mg/L
1,4-Dichlorobenzene	106-46-7	34	mg/L
1,4-Dioxane	123-91-1	9850	mg/L
1-Methylphenanthrene	832-69-9	1	mg/L
2,4,5-Trichlorotoluene	6639-30-1	1	mg/L
2,4,6-Trichlorophenol	88-06-2	3	mg/L
2,4-D	94-75-7	71	mg/L
2,4-Dinitrophenol	51-28-5	11	mg/L
2,4-Dinitrotoluene	121-14-2	24	mg/L
2-Ethoxyethanol	110-80-5	16305	mg/L
2-Methoxyethanol	109-86-4	22655	mg/L
2-Nitropropane	79-46-9	5	mg/L
3,4-Dinitrotoluene	610-39-9	2	mg/L
4,4'-Isopropylidenediphenol	80-05-7	5	mg/L
4,4'-Methylenedianiline	101-77-9	45	mg/L
4-Nitrophenol	100-02-7	41	mg/L
Acetaldehyde	75-07-0	34	mg/L
Acetone	67-64-1	7200	mg/L
Acetonitrile	75-05-8	1640	mg/L
Acrylamide	79-06-1	109	mg/L
Acrylic acid	79-10-7	186	mg/L
Acrylonitrile	107-13-1	10	mg/L
Alachlor	15972-60-8	5	mg/L
Allyl chloride	107-05-1	72	mg/L
Aluminum	7429-90-5	11	mg/L
Aluminum (+3)		3.6	mg/L
Ammonia	7664-41-7	2	mg/L
Ammonium nitrate (solution)	6484-52-2	800	mg/L
Ammonium sulfate (solution)	7783-20-2	4000	mg/L
Aniline	62-53-3	108	mg/L
Anthracene	120-12-7	0.01	mg/L
Antimony	7440-36-0	14.4	mg/L
Antimony cmpds	20-00-8	833	mg/L
Arsenic	7440-38-2	14.4	mg/L
Arsenic cmpds	20-01-9	32	mg/L
Atrazine	1912-24-9	16	mg/L
Barium	7440-39-3	580	mg/L
Barium cmpds	20-02-0	200	mg/L
Benzaldehyde	100-52-7	27	mg/L
Benzene	71-43-2	19	mg/L
Benzoyl chloride	98-88-4	35	mg/L

Table E-11. Fish Lethal Concentration to 50 percent of exposed population (LC_{50})

Chemical	CAS #	Value	unit
Beryllium	7440-90-5	2	mg/L
Biphenyl	92-52-4	2	mg/L
Bis(2-ethylhexyl) adipate	103-23-1	0.35	mg/L
Boron	7440-42-8	113	mg/L
Boron (B III)		113	mg/L
Bromomethane	74-83-9	11	mg/L
Butyl benzyl phthalate	85-68-7	43	mg/L
Butylate	2008-41-5	7	mg/L
Butyraldehyde	123-72-8	32	mg/L
Cadmium	7440-43-9	0.001	mg/L
Cadmium cmpds	20-04-2	0.1	mg/L
Caffeine	58-08-2	151	mg/L
Captan	133-06-2	0.2	mg/L
Carbaryl	63-25-2	8	mg/L
Carbon disulfide	79-15-0	694	mg/L
Carbon tetrachloride	56-23-5	41	mg/L
Carbonyl sulfide	463-58-1	2685	mg/L
Catechol	120-80-9	9	mg/L
Chlorine	7782-50-5	0.34	mg/L
Chlorine dioxide	10049-04-4	0.17	mg/L
Chlorobenzene	108-90-7	17	mg/L
Chloroform	67-66-3	71	mg/L
Chlorophenols [o]	20-05-3	19	mg/L
Chloroprene	126-99-8	2	mg/L
Chlorothalonil	1897-45-6	0.05	mg/L
Chlorpyrifos	2921-88-2	2.4	mg/L
Chromium	7440-47-3	52	mg/L
Chromium (VI)	18540-29-9	22.6	mg/L
Chromium cmpds	20-06-4	33	mg/L
Chromium III	16065-83-1	3.3	mg/L
Cobalt cmpds	20-07-5	0.38	mg/L
Coolant		227634	mg/L
Copper	7440-50-8	0.014	mg/L
Copper (+1 & +2)		0.014	mg/L
Copper cmpds	20-08-6	0.33	mg/L
Cresol (mixed isomers)	1319-77-3	13	mg/L
Cumene	98-82-8	6	mg/L
Cumene hydroperoxide	80-15-9	62	mg/L
Cyanazine	21725-46-2	18	mg/L
Cyanide (-1)	57-12-5	56	mg/L
Cyclohexane	110-82-7	5	mg/L
Cyclohexanone	108-94-1	630	mg/L
Cyclohexylamine	108-91-8	222	mg/L
Decabromodiphenyl oxide	1163-19-5	0.06	mg/L
Di (2-ethylhexyl)phthalate	117-81-7	1	mg/L
Diaminotoluene (mixed isomers)	25376-45-8	37	mg/L
Dibutyl phthalate	84-74-2	1	mg/L
Dichlorobenzene (mixed isomers)	25321-22-6	1	mg/L
Dichloromethane	75-09-2	330	mg/L
Diethanolamine	111-42-2	4710	mg/L

Table E-11. Fish Lethal Concentration to 50 percent of exposed population (LC_{50})

Chemical	CAS #	Value	unit
Diethyl phthalate	84-66-2	32	mg/L
Dimethyl phthalate	131-11-3	121	mg/L
Di-n-octyl phthalate	117-84-0	1	mg/L
Edetic acid (EDTA)	60-00-4	473	mg/L
Epichlorohydrin	106-89-8	35	mg/L
Ethyl chloride	75-00-3	16	mg/L
Ethyl dipropylthiocarbamate	759-94-4	27	mg/L
Ethylbenzene	100-41-4	11	mg/L
Ethylene	74-85-1	14	mg/L
Ethylene glycol	107-21-1	227634	mg/L
Ethylene oxide	75-21-8	84	mg/L
Fluorine	7782-49-2	100	mg/L
Formaldeyde	50-00-0	24	mg/L
Freon 113	76-13-1	290	mg/L
Glycol ethers	111-76-2	1490	mg/L
Glyphosate	1071-83-6	600	mg/L
Hexachloro-1,3-butadiene	87-68-3	0.09	mg/L
Hexachlorobenzene	118-74-1	22	mg/L
Hexachlorocyclopentadiene	77-47-4	0.007	mg/L
Hexachloroethane	67-72-1	1	mg/L
Hexane	110-54-3	2.5	mg/L
Hydrazine	302-01-2	4.83	mg/L
Hydrochloric acid	7647-01-0	19	mg/L
Hydrofluoric acid	7664-39-3	265	mg/L
Hydrogen cyanide	74-90-8	1385	mg/L
Hydroquinone	123-31-9	141	mg/L
Isobutyraldehyde	78-84-2	41	mg/L
Isopropyl alcohol	67-63-0	8623	mg/L
Lead	7439-92-1	31.5	mg/L
Lead cmpds	20-11-1	5	mg/L
Lead sulfate cake	7446-14-2	60.8	mg/L
Lithium salts		2600	mg/L
M,p-xylene		13	mg/L
Malathion	121-75-5	0.1	mg/L
Maleic anhydride	108-31-6	2963	mg/L
Maneb	12427-38-2	2	mg/L
Manganese cmpds	20-12-2	150	mg/L
Mercury	7439-97-6	0.155	mg/L
Mercury cmpds		0.155	mg/L
Metam sodium	137-42-8	0.39	mg/L
Methanol	67-56-1	29400	mg/L
Methl mercury	115-09-3	0.09	mg/L
Methyl chloride	74-87-3	550	mg/L
Methyl ethyl ketone	78-93-3	3220	mg/L
Methyl isobutyl ketone	108-10-1	505	mg/L
Methyl methacrylate	80-62-6	259	mg/L
Methyl parathion	298-00-0	9	mg/L
Methyl tert-butyl ether	1634-04-4	786	mg/L
Methylenebis (phenylisocyanate)	101-68-8		mg/L
Metolachlor	51218-45-2	15	mg/L

Table E-11. Fish Lethal Concentration to 50 percent of exposed population (LC_{50})

Chemical	CAS #	Value	unit
Metribuzin	21087-64-9	80	mg/L
Molybdenum	7439-98-7	157	mg/L
Molybdenum (Mo II, Mo III, Mo IV, Mo V, Mo VI)		157	mg/L
Molybdenum trioxide	1313-27-5	370	mg/L
m-xylene	108-38-3	16	mg/L
N, N-Demethylaniline	121-69-7	65	mg/L
Naphthalene	91-20-3	6	mg/L
N-butyl alcohol	71-36-3	1860	mg/L
Nickel	7440-02-0	2.48	mg/L
Nickel cmpds	20-14-4	27	mg/L
Nitrate		2213	mg/L
Nitrates/nitrites	14797-55-8	2213	mg/L
Nitric acid	7697-37-2	26	mg/L
Nitrites	14797-65-0	225	mg/L
Nitrobenzene	98-95-3	119	mg/L
Nitrogen dioxide	10102-44-0	196	mg/L
N-nitrosodiphenylamine	86-30-6	1	mg/L
o-xylene	95-47-6	16	mg/L
p-cresol	106-44-5	25	mg/L
Phenol	108-95-2	34	mg/L
Phosphoric acid	7664-38-2	70	mg/L
Phosphorus (yellow or white)	7723-14-0	0.02	mg/L
Phthalic anhydride	85-44-9	364	mg/L
Picric acid	88-89-1	170	mg/L
Polychlorinated biphenyls	1336-36-3	3	mg/L
Propionaldehyde	123-38-6	44	mg/L
Propylene	115-07-1	5	mg/L
Propylene oxide	75-56-9	306	mg/L
p-xylene	106-42-3	2	mg/L
Pyridine	110-86-1	100	mg/L
Sec-butyl alcohol	78-92-2	3670	mg/L
Selenium	7782-49-2	4.9	mg/L
Silver	7440-22-4	0.004	mg/L
Silver cmpds		12	mg/L
Silvex	93-72-1	13	mg/L
Sodium Hypochlorite	7681-52-9	0.53	mg/L
Strontium	7440-24-6	210	mg/L
Styrene	100-42-5	4	mg/L
Sulfuric acid	7664-93-9	31	mg/L
Terbufos	13071-79-9	0.01	mg/L
Terephthalic acid	100-21-0	29	mg/L
Tert-butyl alcohol	75-65-0	1954	mg/L
Tetrachloroethylene	127-18-4	17	mg/L
Tin	7440-31-5	626	mg/L
Tin (Sn++, Sn4+)		626	mg/L
Titanium tetrachloride	7550-45-0	25	mg/L
Toluene	108-88-3	34	mg/L
Toluene-2,4-diisocyanate	584-84-9	53	mg/L
Trans-1,2-dichloroethylene	156-60-5	45	mg/L
Trichloroethylene	79-01-6	44	mg/L

Table E-11. Fish Lethal Concentration to 50 percent of exposed population (LC_{50})

Chemical	CAS #	Value	unit
Trichlorofluoromethane	75-69-4	114	mg/L
Triethylene glycol	112-27-6	88100	mg/L
Trifluralin	1582-09-8	0.11	mg/L
Vanadium	7440-62-2	4	mg/L
Vinyl acetate	108-05-4	100	mg/L
Vinyl chloride	75-01-4	143	mg/L
Vinylidene chloride	75-35-4	108	mg/L
Xylene (mixed isomers)	1330-20-7	13	mg/L
Zinc (+2)		0.09	mg/L
Zinc (elemental)	7440-66-6	0.09	mg/L
Zinc cmpds	20-19-9	17	mg/L
Benzo(k)fluoranthene	207-08-9	1000	mg/L
Beta terpineol	138-87-4	5.4	mg/L
Di propylene glycol butyl ether	29911-28-2	930	mg/L
2,2-Dimethylolpropionic acid	4767-03-7	1000	mg/L
Ethoduomeen	53127-17-6	0.5	mg/L
Fluoroboric acid	16872-11-0	1000	mg/L
Fluorosilicic acid	16961-83-4	100	mg/L
Iron pyrite	1309-36-0	1000	mg/L
Tri propylene glycol butyl ether	55934-93-5	900	mg/L
Zinc sulfate	7733-02-0	14	mg/L
Bismuth	7440-69-9	5	mg/L
	Count n=	221	
	Geometric mean=	24.592	
	minimum=	0.001	
	maximum=	227634	

Table E-12. Fish No Observed Effect Level (NOEL)

Chemical	CAS #	Value	unit
1,1,1-Trichloroethane	71-55-6	7	mg/L
1,1,2-Trichloroethane	79-00-5	1	mg/L
1,2,4-Trichlorobenzene	120-82-1	0.2	mg/L
1,2,4-Trimethylbenzene	95-63-6	0.68	mg/L
1,2-Dichlorobenzene	95-50-1	0.05	mg/L
1,2-Dichloroethane	107-06-2	34	mg/L
1,2-Dichloropropane	78-87-5	23	mg/L
1,3-Butadiene	106-99-0	1	mg/L
1,3-Dichloropropene	542-75-6	0.06	mg/L
1,4-Dichlorobenzene	106-46-7	3	mg/L
1,4-Dioxane	123-91-1	2588	mg/L
2,4-D	94-75-7	6	mg/L
2,4-Dinitrophenol	51-28-5	3	mg/L
2,4-Dinitrotoluene	121-14-2	6	mg/L
2-Ethoxyethanol	110-80-5	4076	mg/L
2-Methoxyethanol	109-86-4	5664	mg/L
2-Nitropropane	79-46-9	1	mg/L
4,4'-Isopropylidenediphenol	80-05-7	0.42	mg/L
4,4'-Methylenedianiline	101-77-9	11	mg/L
4-Nitrophenol	100-02-7	10	mg/L
Acetaldehyde	75-07-0	9	mg/L
Acetone	67-64-1	1800	mg/L
Acetonitrile	75-05-8	410	mg/L
Acrylamide	79-06-1	27	mg/L
Acrylic acid	79-10-7	47	mg/L
Acrylonitrile	107-13-1	3	mg/L
Alachlor	15972-60-8	0.51	mg/L
Allyl chloride	107-05-1	18	mg/L
Aluminum (+3)		0.36	mg/L
Ammonia	7664-41-7	0.09	mg/L
Ammonium nitrate (solution)	6484-52-2	40	mg/L
Ammonium sulfate (solution)	7783-20-2	200	mg/L
Aniline	62-53-3	27	mg/L
Antimony	7440-36-0	1.6	mg/L
Antimony cmpds	20-00-8	42	mg/L
Arsenic	7440-38-2	2.1	mg/L
Arsenic cmpds	20-01-9	2	mg/L
Atrazine	1912-24-9	3	mg/L
Barium	7440-39-3	50	mg/L
Barium cmpds	20-02-0	10	mg/L
Benzene	71-43-2	4	mg/L
Benzoyl chloride	98-88-4	9	mg/L
Biphenyl	92-52-4	0.12	mg/L
Bis (2-ethylhexyl)adipate	103-23-1	0.09	mg/L
Boron	7440-42-8	27	mg/L
Boron (B III)		27	mg/L
Bromomethane	74-83-9	3	mg/L
Butyl acrylate	141-32-2	0.31	mg/L
Butyl benzyl phthalate	85-68-7	2	mg/L

Table E-12. Fish No Observed Effect Level (NOEL)

Chemical	CAS #	Value	unit
Butylate	2008-41-5	2	mg/L
Butyraldehyde	123-72-8	8	mg/L
Cadmium	7440-43-9	0.001	mg/L
Captan	133-06-2	0.05	mg/L
Carbaryl	63-25-2	1	mg/L
Carbon disulfide	75-15-0	174	mg/L
Carbon tetrachloride	56-23-5	5	mg/L
Carbonyl sulfide	463-58-1	671	mg/L
Catechol	120-80-9	2	mg/L
Chlorine	7782-50-5	0.02	mg/L
Chlorine dioxide	10049-04-4	0.01	mg/L
Chlorobenzene	108-90-7	2	mg/L
Chloroform	67-66-3	18	mg/L
Chlorophenols [o]	20-05-3	3	mg/L
Chloroprene	126-99-8	0.56	mg/L
Chlorothalonil	1897-45-6	0.01	mg/L
Chlorpyrifos	2921-88-2	0.12	mg/L
Chromium	7440-47-3	5.2	mg/L
Chromium III	16065-83-1	0.33	mg/L
Chromium VI	18540-29-9	2.23	mg/L
Chromium cmpds	20-06-4	2	mg/L
Cobalt cmpds	20-07-5	0.02	mg/L
Coolant	not available	56909	mg/L
Copper	7440-50-8	0.004	mg/L
Copper (+1 & +2)		0.004	mg/L
Copper cmpds	20-08-6	0.02	mg/L
Cresol (mixed isomers)	1319-77-3	3	mg/L
Cumene	92-82-8	0.49	mg/L
Cumene hydroperoxide	80-15-9	16	mg/L
Cyanazine	21725-46-2	5	mg/L
Cyanide (-1)	57-12-5	5.7	mg/L
Cyclohexane	110-82-7	0.39	mg/L
Di (2-ethylhexyl) phthalate	117-81-7	0.08	mg/L
Di-n-octyl phthalate	117-84-0	0.05	mg/L
Diaminotoluene (mixed isomers)	25376-45-8	9	mg/L
Dibutyl phthalate	84-74-2	0.05	mg/L
Dichlorobenzene (mixed isomers)	25321-22-6	0.05	mg/L
Dichloromethane	75-09-2	83	mg/L
Diethanolamine	111-42-2	1178	mg/L
Diethyl phthalate	84-66-2	5	mg/L
Dimethyl phthalate	131-11-3	30	mg/L
Edetic acid (EDTA)	60-00-4	240	mg/L
Epichlorohydrin	106-89-8	9	mg/L
Ethoduomeen	53127-17-6	0.05	mg/L
Ethyl chloride	75-00-3	4	mg/L
Ethyl dipropylthiocarbamate	759-94-4	3	mg/L
Ethylbenzene	100-41-4	1	mg/L
Ethylene	74-85-1	3	mg/L
Ethylene glycol	107-21-1	56909	mg/L

Table E-12. Fish No Observed Effect Level (NOEL)

Chemical	CAS #	Value	unit
Ethylene oxide	75-21-8	118	mg/L
Formaldehyde	50-00-0	6	mg/L
Freon 113	76-13-1	73	mg/L
Glycol ethers	111-76-2	373	mg/L
Glyphosate	1071-83-6	150	mg/L
Hexachlorobenzene	118-74-1	1	mg/L
Hexachloroethane	67-72-1	0.35	mg/L
Hexane	110-54-3	0.25	mg/L
Hydrazine	302-01-2	0.48	mg/L
Hydrochloric acid	7647-01-0	0.95	mg/L
Hydrofluoric acid	7664-39-3	13	mg/L
Hydrogen cyanide	74-90-8	346	mg/L
Hydroquinone	123-31-9	35	mg/L
Isobutyraldehyde	78-84-2	10	mg/L
Isopropyl alcohol	67-63-0	2156	mg/L
Lead	7439-92-1	0.004	mg/L
Lead cmpds	20-11-1	0.26	mg/L
Lead sulfate cake	7446-14-2	6.08	mg/L
Lithium salts		260	mg/L
M,p-xylene	1330-20-7	1	mg/L
m-xylene	108-38-3	2	mg/L
Malathion	121-75-5	0.01	mg/L
Maleic anhydride	108-31-6	741	mg/L
Maneb	12427-38-2	0.09	mg/L
Manganese cmpds	20-12-2	8	mg/L
Mercury	7439-97-6	0.005	mg/L
Mercury cmpds	not applicable	0.005	mg/L
Metam sodium	137-42-8	0.1	mg/L
Methanol	67-56-1	7350	mg/L
Methyl chloride	74-87-3	138	mg/L
Methyl ethyl ketone	78-93-3	805	mg/L
Methyl isobutyl ketone	108-10-1	126	mg/L
Methyl methacrylate	80-62-6	65	mg/L
Methyl parathion	298-00-0	0.88	mg/L
Methyl tert-butyl ether	1634-04-4	197	mg/L
Methylenebis (phenylisocyanate)	101-68-8	16	mg/L
Metolachlor	51218-45-2	1	mg/L
Metribuzin	21087-64-9	20	mg/L
Molybdenum	7439-98-7	0.125	mg/L
Molybdenum (Mo II, Mo III, Mo IV, Mo V, Mo VI)		0.125	mg/L
Molybdenum trioxide	1313-27-5	19	mg/L
N,N-Dimethylaniline	121-69-7	12	mg/L
N-butyl alcohol	71-36-3	465	mg/L
N-nitrosodiphenylamine	86-30-6	0.13	mg/L
Naphthalene	91-20-3	0.59	mg/L
Nickel	7440-02-0	0.09	mg/L
Nickel cmpds	20-14-4	1	mg/L
Nitrate		213	mg/L
Nitrates/nitrites	14797-55-8	213	mg/L

Table E-12. Fish No Observed Effect Level (NOEL)

Chemical	CAS #	Value	unit
Nitric acid	7697-37-2	1	mg/L
Nitrobenzene	98-95-3	30	mg/L
Nitrogen dioxide	10102-44-0	19.6	mg/L
o-xylene	95-47-6	2	mg/L
p-cresol	106-44-5	6	mg/L
p-xylene	106-42-3	0.2	mg/L
Phenol	108-95-2	8	mg/L
Phosphoric acid	7664-38-2	4	mg/L
Phthalic anhydride	85-44-9	91	mg/L
Picric acid	88-89-1	41	mg/L
Polychlorinated biphenyls	1336-36-3	0.14	mg/L
Propionaldehyde	123-38-6	11	mg/L
Propylene	115-07-1	1	mg/L
Propylene oxide	75-56-9	77	mg/L
Pyridine	110-86-1	25	mg/L
Sec-butyl alcohol	78-92-2	918	mg/L
Silver	7440-22-4	0.001	mg/L
Silver cmpds		0.001	mg/L
Styrene	100-42-5	0.44	mg/L
Sulfuric acid	7664-93-9	2	mg/L
Terephthalic acid	100-21-0	7	mg/L
Tert-butyl alcohol	75-65-0	488	mg/L
Tetrachloroethylene	127-18-4	2	mg/L
Tin	7440-31-5	62.6	mg/L
Tin (Sn++, Sn4+)		62.6	mg/L
Titanium tetrachloride	7550-45-0	1	mg/L
Toluene	108-88-3	4	mg/L
Toluene-2,4-diisocyanate	584-84-9	13	mg/L
Trichloroethylene	79-01-6	8	mg/L
Triethylene glycol	112-27-6	8810	mg/L
Trifluralin	1582-09-8	0.01	mg/L
Vinyl acetate	108-05-4	25	mg/L
Vinyl chloride	75-01-4	36	mg/L
Vinylidene chloride	75-35-4	27	mg/L
Xylene (mixed isomers)	1330-20-7	1	mg/L
Zinc (+2)		0.036	mg/L
Zinc (elemental)	7440-66-6	0.036	mg/L
Benzo(k)fluoranthene	207-08-9	0.006	mg/L
Beta terpineol	138-87-4	0.87	mg/L
Di propylene glycol butyl ether	29911-28-2	100	mg/L
2,2-Dimethylolpropionic acid (DMPA)	4767-03-7	100	mg/L
Fluorosilicic acid	16961-83-4	10	mg/L
Iron pyrite	1309-36-0	100	mg/L
Tri propylene glycol butyl ether	55934-93-5	90	mg/L
Zinc sulfate	7733-02-0	0.8	mg/L
Fluoroboric acid	16872-11-0	20	mg/L
Bismuth	7440-69-9	0.5	mg/L
Aluminum	7429-90-5	3.3	mg/L
Beryllium	7440-41-7	0.2	mg/L
Fluorine	7782-41-4	10	mg/L

Table E-12. Fish No Observed Effect Level (NOEL)

Chemical	CAS #	Value	unit
Selenium	7782-49-2	0.1	mg/L
Sodium hypochlorite	7681-52-9	0.05	mg/L
Strontium	7440-24-6	20	mg/L
Vanadium	7440-62-2	0.67	mg/L
	Count n=	199	
	Geometric mean=	3.9012	
	minimum=	0.001	
	maximum=	56909	

Table E-13. Geometric means used to calculate toxicity hazard values [a]				
Parameter	**n**	**min**	**max**	**Geometric mean**
Oral SF	175	0.00095	150000	**0.707**
Inhalation SF	105	0.00165	150000	**1.70**
Oral NOAEL	160	9E-08	3494	**14.0**
Inhalation NOAEL	84	0.006	245000	**68.7**
Fish LC50	221	0.001	227634	**24.6**
Fish NOEL	199	0.001	56909	**3.90**

[a] The chemical data used to generate the geometric means are listed in Tables E-X through E-X.

APPENDIX F:
SUMMARY OF INDUSTRY PERFORMANCE TESTING OF SOLDER

- Bhatia, G, and J. Siegel. "Summary of Lead-Free Solder Performance Based on Existing Data Provided by the Electronics Industry." Report prepared for EPA Design for the Environment Program by Abt Associates, December, 2002.

Appendix F

F.1 INTRODUCTION

F.1.1 SCOPE

This appendix summarizes existing data on the performance of lead-free solders available in the electronics industry. In particular, it considers literature that referenced three specific alternative solder types: tin-copper (Sn-Cu), tin-silver-copper (Sn-Ag-Cu), and tin-silver-copper-bismuth (Sn-Ag-Cu-Bi). Additionally, it includes performance data for the tin-lead (Sn-Pb) alloy, as several literature sources compare alternative alloy data with existing tin-lead standards. This document is intended to provide EPA's Design for the Environment (DfE) *Lead-free Solder Partnership* and other interested parties with a consolidated source of key lead-free solder performance data. It identifies and summarizes existing data as well as documents these sources for further research.

During a preliminary literature search, lead-free solder performance data available in the electronics industry were found to be varied; alloy compositions as well as performance tests carried out on the alternative solders differed. As this appendix intends to be inclusive rather than overlook key applicable results, it includes summaries of documents that reference alloy compositions falling within the alloy families considered (for example, Sn-3Ag-4Cu and Sn-0.5Ag-4Cu fall under the ternary Sn-Ag-Cu alloy family). However, it should be noted that multiple sources have illustrated that performance results vary when an alloy's composition was altered. For example, Lau et al. cite that the elongation of the tin-silver-copper system drops rapidly with increasing bismuth content until it reaches the 3% level, where the elongation decreases slowly and later levels off with a further increase in Bi content. As a result, performance data for alloys were not limited to the compositions as defined by the EPA's DfE *Lead-free Solder Partnership* (see Table F.1.1.1), but included relevant data for alloy compositions close to the Partnership's selection.

Table F.1.1.1: EPA's DfE Lead-free Solder Partnership's Selection: Alloy Compositions and Family

DfE Lead-free Solder Partnership Selection, Alloy Composition	Alloy Family Considered
99.2% Tin and 0.8% Copper	Sn-Cu
95.5% Tin, 3.9% Silver, and 0.6% Copper	Sn-Ag-Cu
96.0% Tin, 2.5% Silver, 0.5% Copper, and 1.0% Bismuth	Sn-Ag-Cu-Bi

F.1.2 BACKGROUND

The Japanese Ministry of International Trade and Industry (MITI) proposed take-back legislation in Japan, requiring consumer and business users to return end-of-life (EOL) equipment to retailers for recycling, making the manufacturer responsible for the cost of recycling. In response to this and other proposed legislation, several major Japanese electronics manufacturers initiated their own roadmaps and publicly announced accelerated plans to eliminate lead-solder from certain or all products. Companies making this commitment included Matsushita, Sony, Toshiba, and Hitachi, with others likely to follow. Currently, Matsushita is successfully marketing lead-free consumer products; Sony has a goal of eliminating lead from products, except for a few uses, by the end of March 2005; and Toshiba's general policy is that all products are available lead-free by the end of 2003. Supplementary to this, published on 13 February, 2003, the European Directive on Waste Electrical and Electronic Equipment (WEEE) requires the substitution of lead, amongst other listed heavy metals, in new electrical and electronic equipment. The Directive is to become effective on 13 August, 2005[1]. These changes in international legislation will potentially eliminate lead from electronic devices produced in the European Union and by foreign competition, thus, driving the implementation of lead-free assembly around the world.

As a result of international legislative and market pressures to phase-out the use of tin-lead solders, the use of lead-free solder alternatives in electronic products manufactured in the U.S. has also received increasing attention. This worldwide shift to lead-free products gives rise to several questions, key among them is the performance of alternative solders. In search of a substitute alloy(s), researchers have conducted numerous performance tests on a host of alternative alloys.

A large number of the alternative solders being considered as a replacement for Sn-Pb are rich in tin and coupled with additional elements to enhance alloy characteristics. Solder performance is determined by testing the alternative solder for characteristics such as joint strength, fatigue resistance[2], and high temperature life. Preliminary literature searches provided some basic information on the elements considered for lead-free solder alloys. For example, silver is comparatively available in abundance, however, it is high in cost. Bismuth poses potential problems with supply as well as embrittlement (as lead contamination drops its melting temperature causing joint embrittlement). Copper on the other hand, is readily available as well as soluble in tin. Additionally, copper-containing tin alloys have been used by the industry in the past.

---

[1] U.K. Department of Trade and Industry, 2005, Sustainable Development and Environment; accessed at: http://www.dti.gov.uk/sustainability/weee/

[2] Fatigue resistance: The maximum stress that a material can endure for a given time without breaking.

F.2 LITERATURE SUMMARY

Research of alternative solders' performance was found to be taking place on a large scale by multi-stakeholder partnerships and industry sectors, academia, and non-regulatory federal agencies (for example, the National Institute of Science and Technology). It was also found that a large number of studies were ongoing with performance data that is yet to be released. For example, the High Density Packaging (HDP) User Group International studies regarding solder reliability characterization was an ongoing research project during the time this appendix was written; results were later released in 2003[3].

The studies that were reviewed for this appendix were found difficult to compare; studies differed in their focus and often considered different alloy combinations and performance tests. Additionally, resulting data were presented in varying metrics. Such disparities in the available data hindered the comparability of performance results across sources.

In order to present these data in the most useful format, a summary of each paper is provided in this section (Section F.2). Select quantitative data from the individual studies have been presented in Section F.3. Qualitative data have been summarized in Section F.4.

It should be noted that these literature sources often referenced more alloys than those summarized. In order to remain within the scope of this document, only those alloys of interest to the Partnership have been presented.

[3] Results became available after the research for this appendix concluded. Results were presented in four papers at the APEX 2003 Conference. The papers presented were: Lead-Free Design, Materials, and Process of High Density Packages, Joe Smetana, Alcatel; Lead-Free Solder Joint Reliability of High Density Packages - Part I: Design For Reliability, Walter Dauksher, Ph.D., Agilent; Lead-Free Solder Joint Reliability of High Density Packages-Part II: Reliability Testing and Data Analysis, John Lau, Ph.D., Agilent Technologies; and Lead-Free Solder Joint Reliability of High Density Packages - Part III: Failure Analysis, Dongkai Shangguan, Ph.D., Flextronics International.

Table F.2.1: List of the Summarized Literature, Solders Addressed, and the Focus of Each Study

Section No.	Title	Authors	Organization	Solders Addressed			Study Focus
				Sn-Cu	Sn-Ag-Cu	Sn-Ag-Cu-Bi	
1.	Electronics Manufacturing with Lead-Free, Halogen Free & Conductive-Adhesive Materials	John H. Lau, C.P. Wong, Ning-Cheng Lee, S.W. Ricky Lee	Agilent Technologies, Inc., Georgia Institute of Technology, Nin-Cheng Lee, Hong Kong University of Science and Technology, respectively	✓	✓	✓	- Physical properties - Mechanical properties - Wetting properties - Reliability properties
2.	Reliability of Solder Joints Assembled with Lead-Free Solder	Masayuki Ochiai, Toshiya Akamatsu, Hidefumi Ueda	Fujitsu Laboratories Ltd., Japan		✓		- Mechanical properties at twisting - Fatigue life subjected to twisting - Solder ball joints of BGA packages - Solder joints of QFPs
3.	The Solder Programme	William J. Plumridge	The Open University Materials Engineering Department, UK	✓	✓		- Tensile properties - Fatigue response - Creep behavior
4.	Mechanical Properties of Sn-3.0mass%Ag-0.5mass%Cu Alloy	Yoshiharu Kariya, William Plumbridge	The Open University Materials Engineering Department, UK		✓		- Tensile behavior - Creep behavior
5.	Properties of Lead Free Alloy and Performance Properties of Lead Free No-Clean Solder Paste	Quan Sheng, Sandy Kwiatek	OMG Americas		✓		- Mechanical properties - Creep performance - Wetting properties (No-clean solder paste system)
6.	Lead-FREE Alloys: Fitting the Square Peg in the Square Hole	Angela Grusd, Chris Jorgensen	Heraeus Cermalloy, IPC - Association Connecting Electronics Industries, respectively	✓	✓		- Physical properties - Creep/Fatigue - Wettability
7.	Research Update: Lead-Free Solder Alternatives	Jasbir Bath, Carol Handwerker, Edwin Bradley	National Electronics Manufacturing Initiative (NEMI)	✓	✓		- Physical properties - Reliability - Reflow and wave soldering - Mechanical properties
8.	AIM: Technical Data Sheet	AIM	AIM	✓	✓		- Mechanical properties - Wetting properties - Fatigue resistance - Solder joint reliability - Wave Soldering and SMT applications
9.	Materials and Process Considerations for Lead-Free Electronics Assembly	Karl Seelig and David Suraski	AIM	✓	✓		- Physical properties - Mechanical properties - Wetting properties - Reliability testing
10.	Database for Solder Properties with Emphasis on New Lead-free Solders	NIST and CSM	National Institute of Standards & Technology (NIST) and Colorado School of Mines (CSM)	✓	✓	✓	- Physical properties - Mechanical properties - Thermal properties

F.2.1 Electronics Manufacturing With Lead-Free, Halogen Free & Conductive-Adhesive Materials

Author(s):	John H. Lau, C.P. Wong, Ning-Cheng Lee, S.W. Ricky Lee
Organization:	by author: Agilent Technologies, Inc., Georgia Institute of Technology, Nin-Cheng Lee, Hong Kong University of Science and Technology, respectively
Publication/Source:	McGraw-Hill, Ch. 13: Prevailing Lead-Free Alloys, p. 13.1-13.62
Date:	September 2000
DfE Alloys Considered:	Sn-Cu, Sn-Ag-Cu, Sn-Ag-Cu-Bi

Summary: This is a comprehensive handbook, covering integrated circuit (IC) packaging, printed circuit board (PCB)/substrates, assembly of IC packages, and novel conductive adhesive materials. Emphasis is on fundamental principles, engineering data, and manufacturing technologies. Among others, this source considers the Sn-Cu, Sn-Ag-Cu and Sn-Ag-Cu-Bi alloys.

Physical properties*:* Eutectic[4] Sn-Cu has the highest melting temperature among prevailing lead-free solders, suggesting greater difficulty in adopting this alloy. The ternary eutectic composition (approximately 95.6Sn-3.5Ag-0.9Cu) has a melting point of 217ºC, while the melting temperature for Sn-Ag-Cu-Bi ranges between 207-216ºC. Sn-Cu is comparable in surface tension, electrical resistivity, and density with Sn-Ag, Sn-Ag-Cu and Sn-Ag-Cu-*X* due to the dominant presence of tin. The hardness however, does vary; that of the ternary alloy is comparable with Sn-Pb. Bismuth-containing alloys on the other hand exhibit considerably higher hardness than Sn-Pb due to the precipitation and Bi-dissolution strengthening mechanisms. (For specific results, see Section F.3, Table F.3.1.a)

Mechanical properties: Eutectic Sn-Cu is lower in tensile strength but higher in elongation than both eutectic Sn-Ag and Sn-Pb, reflecting its softness and ductility. The tensile strength of Sn-Ag-Cu is higher than eutectic Sn-Pb. Near the ternary eutectic point, Sn-Ag-Cu alloys are higher than Sn-Pb in yield strength, shear strength, impact strength, and creep[5] resistance. For Sn-Ag-Cu alloys further away from ternary eutectic composition, the melting temperature (214 to 244ºC) increases, as well as the tensile and shear strengths, at the expense of reduction in elongation. Sn-Ag-Cu-Bi alloys exhibit a higher tensile strength and yield strength, a lower elongation and a slower creep rate as compared to eutectic Sn-Pb. Shear strength of Sn-Cu is comparable with Sn-Pb. The creep strength of Sn-Cu is higher than 100Sn, but lower than Sn-Ag-Cu at both 20 and 100ºC. At 25 and 100ºC, the time to rupture increases in the following order: eutectic Sn-Ag, Sn-Ag-Cu < eutectic Sn-Cu < 60Sn-40Pb. The ternary Sn-3.5Ag-0.75Cu

[4] Eutectic: having the lowest melting point possible. For Sn-Cu this is implies 99.3% Tin and 0.7% Copper.

[5] Creep: under constant load or stress, solder undergoes progressive inelastic deformations over time. This time dependent deformation is called creep.

alloy exhibits the longest time to break in creep tests. The tensile strength and creep resistance of this system increases with an increase in Bi content, then levels off at approximately 7-10% Bi. Elongation of this system, however, drops rapidly with increasing Bi content until it reaches the 3% level, then it decreases slowly and later levels off with additional Bi content. (For specific results, see Section F.3, Tables F.3.1.b and F.3.1.c)

Wetting properties: The wetting properties of eutectic Sn-Cu show great potential as replacements for Sn-Pb in wave and reflow processes. Tests show that the wetting ability of alloys decreases in the following order: eutectic Sn-Pb > Sn-Ag-Cu > Sn-Ag > Sn-Cu when an unactivated flux is used. The difference in wetting diminishes when an activated flux is used and when the wetting time is plotted against superheating. At 260°C, the wetting time descends in the following order: 96Sn-2.5Ag-1Bi-0.5Cu > 96.2Sn-2.5Ag-0.5Sb-0.8Cu > 63Sn-37Pb > 99.3Sn-0.7Cu > 96.5Sn-3.5Ag > 95.5Sn-4Ag-0.5Cu. Wetting time studies conducted by the meniscograph method presented increasing wetting times for solders in the following order: 63Sn-37Pb < Sn-Ag-Cu-2Bi ~ Sn-Ag-Cu-1Bi < Sn-3.5Ag-0.75Cu < Sn-1Ag-0.5Cu < Sn-0.7Cu-0.3Ag < Sn-0.75Cu. However, the wetting time decreases with increasing temperature at a slightly different rate. Finally, both Sn-Ag-Cu-1Bi and Sn-Ag-Cu-2Bi were found to display wetting behavior that is fairly comparable with 63Sn-37Pb.

The reflow spreading of eutectic Sn-Cu is better than eutectic Sn-Ag, but poorer than eutectic Sn-Pb. Studies presented the following spreading behavior in decreasing order: 63Sn-37Pb > Sn-Ag-Cu-4.5Bi, Sn-Ag-Cu-7.5Bi > Sn-3.5Ag-0.75Cu > 99.25Sn-0.75Cu. This source states that preferably the use of eutectic Sn-Cu should be confined to wave soldering. Varying references ranged wetting times for the Sn-Ag-Cu alloy from 0.23 to 1.1 seconds, while spreading behavior ranged between 3.9 to 5 and contact angle ranged between 21 to 47 degrees. The presence of Bi significantly improves the solder spreading properties of lead-free solders. The Sn-Ag-Cu-Bi system is outstanding in creep resistance and wetting. (For specific results, see Section F.3, Table F.3.1.d)

Reliability: The tensile strength of the eutectic Sn-Cu is fairly poor, however its fatigue resistance is fairly good. One study showed fatigue resistance to increase in the following order: 63Sn-97Pb < 64Sn-36In < 58Bi-42Sn < 50Sn-50In < 99.25Sn-0.75Cu < 100Sn < 96Sn-4Cu. However, the low-cycle isothermal fatigue (strain 0.2%, 0.1 Hz, R=0.8, 300 K) performance shows that the number of cycles to failure for eutectic Sn-Cu is less than one-third of that for eutectic Sn-Pb, while ternary 95.4Sn-3.1Ag-1.5Cu is significantly greater. For the two cases in this study which compared Sn-Cu with Sn-Pb, Sn-Cu is consistently better. For a 12-mm, 144-flexible ball grid array (fleXBGA) assembly at different cycling temperatures, Sn-Ag was the best, with low or no failure rates. The ternary Sn-4Ag-0.5Cu and Sn-3.4Ag-0.7Cu are similar to each other and also have better performance than eutectic Sn-Pb. At -40 to 125°C cycling, however, Sn-Cu performs similarly to Sn-Pb and little improvement is shown for Sn-Ag-Cu over Sn-Pb. In this range, eutectic Sn-Ag is again the best performer. For temperature cycling performance in ball grid array (BGA) assembly, eutectic Sn-Ag appears to be superior to Sn-Cu,

but the opposite is observed for flip-chip assembly. It was reported that the thermal fatigue[6] life for flip-chip assembly descends in the following order: eutectic Sn-Cu > Sn-3.8Ag-0.7Cu, eutectic Sn-Pb > eutectic Sn-Ag.

The presence of Bi in the lead-free alloys can form a 52Bi-30Pb-18Sn ternary eutectic structure in the solidified solder joint which has a melting temperature of 96ºC. This can be a concern because the solder joints become weak when subjected to thermal cycling. Lau et al., present additional data on temperature cycling and heat treatment reliability for Sn-Ag-Cu as well as Sn-Ag-Cu-Bi. In all the reported results, the Sn-Ag-Cu system is the prevailing alternative to lead-containing solder. (For specific results, see Section F.3, Tables F.3.1.a to F.3.1.d)

F.2.2 Reliability of Solder Joints Assembled with Lead-Free Solder

Author(s):	Masayuki Ochiai, Toshiya Akamatsu, Hidefumi Ueda
Organization:	Fujitsu Laboratories Ltd., Atsugi, Japan
Publication/Source:	Fujitsu Science Technology Journal, **38**, 1, p. 96-101
Date:	June 2002
DfE Alloys Considered:	Sn-Pb, Sn-Ag-Cu

Summary: The dynamic mechanical properties and reliability of Sn-Ag-Cu were tested in this study. Compared to the eutectic Sn-Pb solder, the ternary alloy was found harder to deform and more resistant to hardening, thus having a longer fatigue life.

Dynamic mechanical properties at twisting, temperature dependence: The shear modulus (similar to Young's modulus for tension, but indicates the ratio of a shear stress to its resulting shear strain) of both Sn-Pb and Sn-Ag-Cu decreased with rising temperature. The tin-lead alloy, however, had a much larger rate of decrease than the ternary alloy, showing that the former softens faster than the latter with increasing temperatures. It was also found that the Sn-Ag-Cu solder is more difficult to deform and less likely to harden than the Sn-Pb solder; therefore, it has a longer fatigue life.

Influence of twisting velocity on dynamic mechanical properties: The tin-lead solder was found to deform easily at twisting velocities below 1 rad/s (i.e., the range of twisting velocities that solder joints are subjected to in normal equipment operation). The ternary alloy was shown to be difficult to deform plastically and thus less likely to harden.

Fatigue life of solders subjected to twisting cycles: The fatigue life of Sn-Ag-Cu solder was approximately 10,000 cycles, almost twice the fatigue life of the Sn-Pb solder. These results again indicate that compared to the tin-lead solder, Sn-Ag-Cu is harder to deform plastically and therefore less likely to harden. This suggests that the ternary alloy has sufficient fatigue

[6] Thermal fatigue: premature failure resulting from cycling stresses due to temperature changes.

resistance for use in electronics assembly.

Solder ball joints of BGA (Ball Grid Array) packages during transition to lead-free soldering: While in transition, lead and lead-free solders will be used combined in BGA ball joints. Mixing Sn-Ag-Cu solder with Sn-Pb was found to reduce the fatigue life slightly, maintaining its superiority to that of the Sn-Pb solder. This suggests sufficient reliability for the mixed solder joint.

Solder joints of QFPs (Quad Flat Pack) after transition to lead-free soldering: After the transition, QFP leads will be plated with lead-free solder, contaminating the joints with lead-free solder plating. A plating composition of Sn-2Bi presented an approximate 30% reduction in fatigue life in the Sn-Ag-Cu solder. However, the fatigue life was still superior to that of the Sn-Pb solder. It was concluded that Sn-Ag-Cu solder joints, with an expected level of bismuth contamination, will have a fatigue life comparable to current Sn-Pb solder joints. (For specific results, see Section F.3, Table F.3.2)

F.2.3 The Solder Programme at the Open University Materials Engineering Department: An Update, 2001

Author(s):	William J. Plumbridge
Organization:	Materials Engineering Department, The Open University, Buckinghamshire, U.K.
Publication/Source:	Materials Engineering Department, The Open University, UK. (http://technology.open.ac.uk/materials/mat-hp.html)
Date:	2001
DfE Alloys Considered:	Sn-Pb, Sn-Cu, Sn-Ag-Cu

Summary: The Open University program has been directed towards the testing performance of solder joints. This source briefly reviews the background and current status of the research into solder alloys and solder interconnections for use in electronics. It presents in-depth results for fatigue, creep and fatigue-creep interactions at high temperatures. It considers the Sn-0.5Cu and ternary Sn-3.8Ag-0.7Cu alloys.

Tensile Properties: The behavior of the referenced alloys was tested at temperatures between -10 and 75°C and strain rates between 10^{-1} and $10^{-6}s^{-1}$. Temperature and strain rate were found to have a substantial effect on strength. Raising the temperature from -10 to 75°C was found to reduce the tensile strength by approximately 75% of its value at -10°C (for example, the Sn-Pb and Sn-Cu alloys fell below 10 MPa at 75°C with a strain rate of $10^{-6}s^{-1}$). Ductility trends with temperature and strain rate were seen to be small and inconsistent. The Sn-Ag-Cu and Sn-Ag alloys display the smallest elongation to failure although the ductility values of all the alloys fall between 20 and 55%. The Sn-0.5Cu solder is usually the weakest and most ductile of the tested alloys, whereas comparatively, the Sn-Ag-Cu alloy is the strongest (with strength being greatest at -10°C with the fastest straining rates). This paper finds that the "inter-relationships between

strength, ductility, temperature and strain rate are complex, and the relative merits of the alloys may change according to the test conditions."

Fatigue Response: Fatigue tests were carried out at room temperature and at 75°C on Sn-37Pb, Sn-0.5Cu, and Sn-3.5Ag, exhibiting softening (around 15-20%) when subjected to strain controlled cycling. The incorporation of a dwell in the strain cycle reduces the number of cycles to failure in comparison with continuous cycling, irrespective of the dwell location. Generally, longer dwells result in lower numbers of cycles to failure, with balanced dwells resulting in the shortest life times.

Creep Behavior: Creep testing was carried out between -50°C and 130°C and times to rupture were examined up to several thousand hours. The creep behavior of the Sn-0.5Cu alloy is similar to that of Sn-37Pb at 75°C, while Sn-Ag-Cu exhibits much greater creep resistance that appears to increase at lower stress levels. Both the silver-containing alloys exhibit a much greater creep resistance than Sn-37Pb, appearing to increase at lower stress levels. This superior creep performance is intrinsic to the alloy, as greater life is retained when testing at the same homologous temperatures to non-silver alloys. At high temperatures (for example, 99°C), the rupture time of the silver-containing alloys are extremely sensitive to stress, where minor changes in service conditions could result in profound consequences on creep life. Lead-free alloys show lower creep ductility as compared with the eutectic Sn-37Pb (approximately 40%) at 75°C. The creep ductility of the silver-containing alloys is the lowest at around 20%, and appears to be unaffected by applied stress.

Tin Pest: Tin pest can be found in the Sn-0.5Cu alloy when stored for over a year at temperatures below 13°C. Here white tin transforms to grey tin with a substantial increase in volume, resulting primarily in surface wart formation and cracking, and finally in complete disintegration. (For specific results, see Section F.3, Table F.3.3)

F.2.4 Mechanical Properties of Sn-3.0mass%Ag-0.5%mass%Cu Alloy

Author(s):	Yoshiharu Kariya and William J. Plumbridge
Organization:	Materials Engineering Department, The Open University, Buckinghamshire, U.K.
Publication/Source:	Materials Engineering Department, The Open University, U.K.
Date:	Not Provided
DfE Alloys Considered:	Sn-Ag-Cu

Summary: This paper investigates the tensile and creep behavior of Sn-3.0Ag-0.5Cu in the rapidly cooled, as-cast state, and compares it with Sn-3.8Ag-0.7Cu and Sn-3.5Ag. Temperature for the tensile tests ranged between 263K and 398K, and the constant load creep tests were performed at 348K.

The ternary alloys, Sn-3.0Ag-0.5Cu and Sn-3.8Ag-0.7Cu, were found to have similar tensile

strengths, where tensile strength was found to decrease with increasing temperature and with decreasing strain rate. The tensile strength for the former alloy was 20% higher than Sn-3.5Ag and double that observed in Sn-0.5Cu at a strain rate of 10^{-3}/s and 348K. Both Sn-3.0Ag-0.5Cu and Sn-3.8Ag-0.7Cu were shown to be superior to the Sn-3.5Ag alloy in this characteristic.

The creep resistance of both the ternary alloys were found to be comparable to each other and clearly superior to the Sn-Ag alloy. Applied stress had little effect on the creep ductility of the alloys, with the creep ductility of Sn-3.0Ag-0.5Cu being almost equivalent to eutectic Sn-Ag and the standard Sn-Ag-Cu for this property. (For specific results, see Section F.3, Table F.3.4)

F.2.5 Properties of Lead Free Alloy and Performance Properties of Lead Free No-Clean Solder Paste

Author(s):	Quan Sheng, Charles Bradshaw, Sandy Kwiatek
Organization:	OMG Americas, Research Triangle Park, NC
Publication/Source:	Presented at IPC SMEMA Council APEX® 2002 (www.goapex.org)
Date:	2002
DfE Alloys Considered:	Sn-Pb, Sn-Ag-Cu

Summary: This paper examines the development of a no-clean solder paste system with the unique needs of the 214-220ºC melting point of lead-free alloys. The properties of the Sn-3.5Ag-0.5Cu no-clean solder paste are compared to 63Sn-37Pb no-clean solder paste.

Mechanical properties of the two alloys compared favorably, showing slightly lower ultimate tensile strength and yield strength for the lead-free alloy. Elongation results were inconsistent for the two alloys. Creep performance of the ternary alloy in bulk was found to be superior to the 63Sn-Pb alloy. Wetting properties of solder joints made with both pastes were found to be comparable. Both alloys demonstrated similar static viscosity, dynamic viscosity, tack, printability, solderability, wide reflow window, and reflow characteristics. Finally, the lead-free no-clean paste was found to potentially have a longer print life than 63Sn-Pb. From a performance standpoint, lead-free no-clean Sn-3.5Ag-0.5Cu paste has similar characteristics to 63Sn-Pb, and could be used for PCB applications. (For specific results, see Section F.3, Table F.3.5)

F.2.6 Lead-FREE Alloys: Fitting the Square Peg in the Square Hole

Author(s):	Angela Grusd and Chris Jorgensen
Organization:	Heraeus Cermalloy and IPC - Association Connecting Electronics Industries
Publication/Source:	Circuitree, p. 98-102
DfE Alloys Considered:	September 1999
DfE Alloys Considered:	Sn-Cu, Sn-Ag-Cu

Summary: This paper provides an overview of numerous lead-free alloys, examining temperature ratings, cost, and other factors. It notes that two alloys–99.3Sn-0.7Cu and 95.5Sn-4.0Ag-0.5Cu–have mid-range melting temperatures (i.e. between 200°C-230°C), slightly higher than that of tin-lead, and have been popular choices in the industry, particularly in the case of reflow soldering.

Tin-Copper: The melting temperature for this alloy (99.3Sn-0.7Cu) is 227°C. This alloy may prove suitable for high-temperature applications such as those required by the automotive industry. Testing shows significant improvement in creep/fatigue data over Sn-Pb alloy. However, the Sn-Ag-*X* alloys are found to perform better in creep testing.

Tin-Silver-Copper: The melting temperature for this alloy (95.5Sn-4.0Ag-0.5Cu) falls between 217-219°C. This temperature range makes it well-suited for high operation temperatures (up to 175°C). The mechanical stability of the joint is degraded when the melting point of the solder is approached. Thus, elevated temperature cycling produces less damage with higher melting point solders than it does for Sn-Pb solders (melting point of 183°C). These solders however, do not wet copper as well as the eutectic Sn-Pb solder using commercial fluxes. However, if the fluxes are suited for high-temperature use, good fillet formation can be achieved. Wettability can also be improved using no-clean fluxes when soldering in nitrogen atmosphere. This paper points out that there are other factors besides performance, such as cost, to consider when selecting a lead-free alloy. (For specific results, see Section F.3, Table F.3.6)

F.2.7 Research Update: Lead-Free Solder Alternatives

Author(s):	Jasbir Bath, Carol Handwerker, Edwin Bradley
Organization:	National Electronics Manufacturing Initiative (NEMI)
Publication/Source:	Circuits Assembly (www.circuitassembly.com), p. 31-40.
Date:	May 2000
DfE Alloys Considered:	Sn-Cu, Sn-Ag-Cu

Summary: This paper identifies Sn-3.9Ag-0.6Cu as the recommended choice for reflow soldering, and Sn-0.7Cu or Sn-3.5Ag as the recommended choices for wave soldering. It provides an update on current research for lead-free solder alternatives, and makes note that further investigations are being conducted on the alternative alloys.

Tin-Copper: The eutectic alloy Sn-0.7Cu has a melting temperature of 227°C. Reliability data indicates it is similar to Sn-37Pb for surface-mount use. Due to a melting temperature 10°C higher than the ternary Sn-Ag-Cu alloy, Sn-0.7Cu is found undesirable for reflow applications. This temperature does not present the same concern for wave soldering applications. This paper makes note of a tendency for fillet lifting when using tin-silver, tin-copper or tin-silver-copper alloys for wave soldering with lead containing surface finishes, due to the presence of lead. A significant advantage to using Sn-0.7Cu is the low cost of bar solder.

Tin-Silver-Copper: Alloys within this family with a melting range between 217°C and 222°C are good substitutes for tin-lead solder. The European IDEALS consortium recommended the Sn-3.8Ag-0.7Cu alloy as the best lead-free alloy for reflow. Reliability for this alloy composition was found equivalent to or better than the Sn-Pb and Sn-Pb-Ag alloys.

Within this ternary alloy family, several readily available alloys–Sn-3.5Ag-0.7Cu, Sn-3.6Ag-0.9Cu, Sn-3.8Ag-0.7Cu, as well as Sn-4Ag-0.5Cu--have melting temperatures near 217°C. Alloy compositions within the range of Sn-3.5 to 4% (weight) Ag-0.5 to 1% (weight) Cu are close enough to the eutectic to have similar liquidus[7] temperatures, microstructures and mechanical properties. Bath et al. note that results from literature and solder vendors indicate that the solderability of the ternary alloy is adequate, however, like all lead-free alloys, worse than eutectic Sn-Pb.

The NEMI Lead-Free Task Force decided on the Sn-3.9Ag-0.6Cu solder as their recommendation to the industry for reflow soldering. For wave soldering the recommended choices are Sn-0.7Cu and Sn-3.5Ag. The NEMI Lead-Free Task Force is continuing to investigate the performance of these substitutes. Updated information can be found on the NEMI web page: http://www.nemi.org/newsroom/Presentations/index.html. (For specific results, see Section F.3, Table F.3.7)

F.2.8 AIM: Technical Data Sheet

Organization:	AIM (a global manufacturer of electronics soldering materials)
Publication/Source:	AIM: Technical Articles: Lead-free Product Data Sheets (http://www.aimsolder.com/leadfree_tdss.cfm?section=assembly)
Dated:	Not Provided
DfE Alloys Considered:	Sn-Cu, Sn-Ag-Cu

Summary: AIM's Technical Data Sheets present the characteristics of select lead-free solder alloys. The alloys relevant to the scope of this study are: Sn-0.7Cu, Sn-3Ag-0.5Cu (LF218™), and Sn-3.8-4.0Ag-0.5-0.7Cu (TSC-4).

Tin-Copper: The Sn-0.7Cu alloy is high in purity with a high melting temperature of 227°C.

[7] Liquidus: the lowest temperature at which a metal or alloy is completely liquid.

This eutectic alloy can be used for high temperature lead-free applications.

Tin-Silver-Copper: The Sn-3.8-4.0Ag-0.5-0.7Cu alloy has a low melting point of 217-218ºC, good wetting properties, excellent fatigue resistance, excellent solder joint reliability and is compatible with all flux types. The Sn-3Ag-0.5Cu (LF218™) alloy also has a melting point of 217-218ºC and falls under the JEIDA recommendation for lead-free soldering. These two ternary alloys are near drop-in replacements for eutectic Sn-37Pb in both wave and hand soldering applications. In wave soldering, both these alloys produce less dross than other solder alloys, wet well, and provide superior joint strength. In SMT (Surface-Mount Technology) applications, they produce stronger solder joints, have greater mechanical fatigue resistance, and are good substitutes for the eutectic tin-lead alloy. Additionally, the Sn-3Ag-0.5Cu and Sn-3.8-4.0Ag-0.5-0.7Cu no-clean solder pastes pass all Bellcore and IPC specifications. (For specific results, see Section F.3, Table F.3.8)

F.2.9 Materials and Process Considerations for Lead-Free Electronics Assembly

Author(s):	Karl Seelig[8] and David Suraski
Organization:	AIM
Publication/Source:	AIM: Lead-free Articles (http://www.aimsolder.com/lead_free.cfm?section=articles#2)
Date:	Not provided
DfE Alloys Considered:	Sn-Cu, Sn-Ag-Cu

Summary: This paper presents analyses of tin-silver, tin-copper, and tin-silver-copper alloys and compares reliability testing results and process considerations for them. In order to obtain reliability results, the alloys were subjected to various thermal and mechanical fatigue tests. The paper also briefly discusses cost and patent issues related to these solders.

Tin-Copper: While tin-copper solders may be less costly than those containing silver, there are other issues to consider. The Sn-0.7Cu alloy has a melting temperature of 227ºC, prohibiting its use for many temperature-sensitive applications. It is also a poor wetting alloy compared to other lead-free solders. This could require the use of nitrogen and aggressive fluxes for many applications and may result in wetting-related defects. Additionally, Sn-Cu typically has lower capillary action to draw it into barrels during Plated Through Hole (PTH) Technology and lacks the fatigue resistance needed for surface mount assembly. Finally, the poor fatigue characteristics of this alloy may result in field failures, which negates initial cost savings provided by this less-expensive alloy.

Tin-Silver-Copper: Most of the world seems to be looking to the Sn-Ag-Cu family of alloys as a

[8] Note: Karl Seelig, AIM, has provided a number of technical papers presenting results of lead-free solder alloys, often presenting overlapping data. It should also be noted that Table F.3.9 combines performance data from several of these sources (including literature not summarized in this appendix, but listed under *References*).

substitute for lead solder alloys. The Sn-4Ag-0.5Cu alloy has a melting point of 218^{o}C and its base materials are abundantly available. It offers very good fatigue characteristics and good overall joint strength. Wetting tests demonstrate that alloys with lower silver contents (for example, Sn-2.5Ag-0.7Cu-0.5Sb) wet stronger and faster than those with higher silver contents (for example, Sn-4Ag-0.5Cu). However, the silver content of this alloy makes it cost prohibitive for some applications. Further, silver-containing alloys have experienced failure during fatigue testing, due to a phase change which causes structural weakness. The low silver alloys can reduce this problem and offer improved wetting and slightly lower melting temperatures. The low silver alloys are available worldwide, provide the advantages of the Sn-Ag-Cu family of alloys, are less cost prohibitive, and avoid the problems associated with Sn-Cu and dual-alloy processes.

Dual Alloy Assembly: Apart from problems associated with Sn-Cu, intermixing Sn-Ag-Cu and Sn-Cu solders may result in non-uniformly alloyed solder joints. This may cause the joint to be susceptible to fatigue failure due to inability to relieve stress and strain. Further, when repairs or touch-ups are needed, two inventories of alloys are required and operators must be sure not to mix the alloys.

Reliability - Thermal Cycling Testing: Test boards were built using Sn-0.7Cu and Sn-4Ag-0.5Cu in conjunction with 1206 thin film resistors. The boards were thermally shocked from -40 to 125^{o}C for 300, 400 and 500 15-minute cycles. Post-test inspections show that the Sn-Cu alloy exhibited some cracked solder joints as a result of poor wetting. In addition, well-formed solder joints made from the Sn-Cu alloy also showed cracks on the third set of boards cycled to 500 repetitions. The Sn-4Ag-0.5Cu alloy on the other hand, did not show any cracks during testing up to 500 repetitions, demonstrating that it has significantly superior thermal fatigue resistance as compared to Sn-Cu. However, it should be noted that the Sn-4Ag-0.5Cu alloy did exhibit some change in grain structure throughout the joint subsequent to the thermal cycling.

Mechanical Strength-Flex Testing: To test the solders' mechanical strength, test boards were built using the two alloys in conjunction with 1206 thin film resistors, and were subjected to flex testing. The test results show that solder joints produced from Sn-0.7Cu cracked during flex testing, indicating a weak joint that is unable to withstand a wide range of mechanical stresses. On the contrary, solder joints produced from Sn-4Ag-0.5Cu passed all flex test requirements. (For specific results, see Section F.3, Table F.3.9)

F.2.10 Database for Solder Properties with Emphasis on New Lead-free Solders Release 4.0

Organization:	National Institute of Standards & Technology (NIST) and Colorado School of Mines (CSM)
Publication/Source:	Properties of Lead-Free Solders (http://www.boulder.nist.gov/div853/lead%20free/props01.html)
Dated:	February 11, 2002 (last updated)
Alloys Considered:	Sn-Pb, Sn-Cu, Sn-Ag-Cu, Sn-Ag-Cu-Bi

Summary: This database summarizes the mechanical and thermal properties of lead-free alloys from numerous sources. These data were summarized in a series of tables. Excerpts of these tables have been presented in Section F.3, illustrating the properties of the tin-lead solder along with three lead-free solders in compositions identical or similar to those being examined by the DfE Partnership.

This source presents data on the shear strengths and wetting angles; mechanical properties such as ductility, tensile, physical; and thermal properties of multiple solder alloy compositions. (For specific results, see Section F.3, Tables F.3.10.a. through F.3.10.g)

F.3 PERFORMANCE TABLES

Table F.3.1.a: Physical Properties of Lead-free Solders, Summary Table

Alloy Family	Sn-Pb	Sn-Cu	Sn-Ag-Cu			Sn-Ag-Cu-Bi
Alloy Composition	63Sn-37Pb	99.3Sn-0.7Cu	95.5Sn-3.8Ag-0.7Cu	95.5Sn-4Ag-0.5Cu	95.4Sn-3.1Ag-1.5Cu	93.3Sn- 3.1Ag-3.1Bi-0.5Cu
Melting Temperature (^oC)	183	227	217	217-255	216-217	209-212
Surface Tension (dyne/cm)	380 at 260^oC, 417 at 233^oC (air), 464 at 233^oC (nitrogen)	491 at 277^oC (air), 461 at 277^oC (nitrogen)	–	–	–	–
Density (gm/cm^3)	8.36, 8.4	7.31	7.5	7.44, 7.39	–	7.56 (Sn-2Ag-0.5Cu-7.5Bi)
Thermal Conductivity ($W/cm\cdot^oC$)	0.509 at 30^oC, 0.50 at 85^oC	–	–	–	–	–
Electrical Resistivity (μO-cm)	14.5, 15.0, 17	10-15	13	10-15		10.6 (Sn-3Ag-3Cu-2Bi)
Hardness (Vickers hardness, kg/mm2 (HV); Brinell hardness (BH))	12.8 (HV), 17 (BH)	–	15 (BH)	–	–	34.5 (Sn-3Ag-3Cu-2Bi)
CTE (ppm)	18.74, 25, 21, 24	–	14.83 (Sn-3Ag-4Cu)	–	–	–

Source: Lau et al., "Electronics Manufacturing With Lead-Free, Halogen Free & Conductive-Adhesive Materials," September 2000.

– where alloys had no performance data.

CTE Coefficient of Thermal Expansion

Table F.3.1.b: Creep Behavior of Lead-free Solders, Summary Table

Alloy Family		Sn-Pb	Sn-Cu	Sn-Ag-Cu	Sn-Ag-Cu-Bi
Alloy Composition		63Sn-37Pb	99.3Sn-0.7Cu	95.5Sn-3.8Ag-0.7Cu	93.3Sn-3.1Ag-3.1Bi-0.5Cu
Creep Strength at 0.1 mm/min (N/mm^2)	20°C	–	8.6	13	–
	100°C	–	2.1	5	–
Creep at 25°C (MPa)	100h to failure	6 (Sn-40Pb)	–	27 (Sn-4Ag-0.5Cu)	–
	1000h to failure	2.8 (Sn-40Pb)	–	7.5 (Sn-4Ag-0.5Cu)	–
Time to break (MPa)		–	–	323 (Sn-1Ag-0.5Cu); 3,849 (Sn-3.5Ag-0.75Cu)	218 (Sn-Ag-Cu-7.5Bi); 1747 (Sn-Ag-Cu-4.5Bi); 2203 (Sn-Ag-Cu-2Bi)
Number of Cycles to failure*		3,650	1,125	8,936 (95.4Sn-3.1Ag-1.5Cu)	6,522

Source: Lau et al., "Electronics Manufacturing With Lead-Free, Halogen Free & Conductive-Adhesive Materials," September 2000.

* Relative performance in Fatigue Resistance of lead-free solders in low-cycle isothermal fatigue test (strain 0.2%; 0.1 Hz; *R*=0.8; 300K).

Table F.3.1.c: Mechanical Properties of Lead-free Solders, Summary Table

Alloy Family			Sn-Pb	Sn-Cu	Sn-Ag-Cu	Sn-Ag-Cu-Bi
Alloy Composition			63Sn-37Pb	99.3Sn-0.7Cu	95.5Sn-3.8Ag-0.7Cu	93.3Sn-3.1Ag-3.1Bi-0.5Cu
Ultimate Tensile Strength (MPa)			19-56*	23	48; 48.5 (95.4Sn-3.1Ag-1.5Cu)	78
Yield Strength (MPa)			27.2-37**	37	45	85.3 (Sn-2Ag-7.5Bi-0.5Cu)
Young's Modulus (GPa)			38.1 (-70°C), 30.2 (20°C), 19.7 (140°C), 32, 33.58, 35, 15.7, 31.03	–	–	–
Elongation (%)			31-58.87***, 35-176****	45	36.5 (95.4Sn-3.1Ag-1.5Cu)	19
Shear Strength (MPa)	at 0.1 mm/min	20°C	23	20-23	27	–
		100°C	14	16-21	17	–
	at 0.1 mm/min; gap thickness: 76.2µm; cooling rate =10^6/s	22°C	36.5 (Sn-40Pb)	29.8	63.8	–
		170°C	4.5 (Sn-40Pb)	10.1	25.1	–
	at 1 mm/min at reflow temperature (RT)		34.5 (Sn-40Pb)	28.5 (Sn-1Cu)	–	–
	at 1 mm/min at 100°C		21.6 (Sn-40Pb)	21.2 (Sn-1Cu)	–	–
	By ring-and-plug test		40.27	–	–	–
Impact Strength (J/cm^2)			31	–	77 (Sn-3.5Ag-0.75Cu)	–

Source: Lau et al., "Electronics Manufacturing With Lead-Free, Halogen Free & Conductive-Adhesive Materials," September 2000.

* The ultimate tensile strength values fall between 19 and 56 MPa (with an average of 39.47 MPa) as per ten references cited by Lau et al., Table 13.2.

** The yield strength values fall between 27.2 and 37 MPa (with an average of 30.62 MPa) as per four references cited by Lau et al., Table 13.2.

*** The elongation values fall between 31 and 52.87% (mean 41.0%) as per six references cited by Lau et al., Table 13.2.

**** The elongation value according to a reference cited by Lau et al., Table 13.2, ranged between 35-176 percent.

Table F.3.1.d: Wetting Properties of Lead-free Solders, Summary Table

Wetting Properties							
Alloy Family			**Sn-Pb**		**Sn-Ag-Cu**		**Sn-Ag-Cu-Bi**
Alloy Composition			60Sn-40Pb	62Sn-38Pb	95.5Sn-3.8Ag-0.7Cu	95.5Sn-4.7Ag-1.7Cu	Sn-3.3Ag-3Bi-1.1Cu
Contact Angle (degrees)	–		17	–	–	21	–
	Flux A611, 260-280°C		22	–	–	47	–
	Flux A260HF, 260-280°C		32	–	–	45	–
	Flux B2508, 260-280°C		31	–	–	35	–
Wetting Time at 260°C (seconds)	Immersion Pb PCB		–	0.36 (at 235°C)	0.28	–	0.24
	Immersion Sn PCB		–	0.27 (at 235°C)	0.23	–	0.26
	Immersion Ag PCB		–	0.20 (at 235°C)	0.25	–	0.19
	NiAu, PCB		–	0.32 (at 235°C)	0.42	–	0.44
	OSP 1		–	0.20 (at 235°C)	0.26	–	0.26
	OSP 2		–	0.21 (at 235°C)	0.23	–	0.25
	OSP 3		–	0.24 (at 235°C)	0.27	–	0.27
Spread	OSP 3	A	–	4.55	4.2	–	4
		B	–	5	4.35	–	4.45
	Immersion Ag	A	–	4.7	4.55	–	4.6
		B	–	4.7	4.8	–	4.95
	Immersion Pd	A	–	4.4	3.9	–	4.4
		B	–	4.7	3.9	–	4.65
	NiAu	A	–	5	4.4	–	4.7
		B	–	5	5	–	5

Source: Lau et al., "Electronics Manufacturing With Lead-Free, Halogen Free & Conductive-Adhesive Materials," September 2000.

Key:
A Peak 240°C, dwell 60-s for Pb-free, 215°C, 60-s dwell for Sn-Pb-Ag, scale 1 to 5 (best), forced-air convection, air.
B Peak 240°C, dwell 60-s for Pb-free, 215°C, 60-s dwell for Sn-Pb-Ag, scale 1 to 5 (best), 230°C bp VPR.

Table F.3.2: Tin-Silver-Copper Solder Joint Reliability Compared with Sn-Pb, Summary Table

Alloy Family	Temperature Dependence				QFP solder joints
	Shear Modulus (at increasing temperature)	**Deformation** (twisting velocity below 1 rad/s)	**Hardening**	**Fatigue life**	**Fatigue life**
Sn-Pb	decreases (at a larger rate than Sn-Ag-Cu)	easily deformed	–	–	–
Sn-Ag-Cu	decreases (at a smaller rate than Sn-Pb)	more difficult to deform (than Sn-Pb)	less likely to harden (than Sn-Pb)	10,000 cycles (almost twice Sn-Pb)	superior (to Sn-Pb) with controlled Bi-contamination

Source: Ochiai et al., "Reliability of Solder Joints Assembled with Lead-Free Solder"

Table F.3.3: Tensile, Fatigue, and Creep Properties of Lead-free Alloys, Summary Table

Alloy Family	Tensile Properties			Fatigue Tests*	Creep Properties**	
	Elongation to Failure	**Ductility**	**Tensile Strength*** **		**Creep Behavior (at 75°C)**	**Time to Rupture**
Sn-Pb	–	–	below 10MPa	softening (15-20%)	–	–
Sn-Cu	–	comparatively most ductile	below 10MPa (weakest)	softening (15-20%)	similar to Sn-37Pb	lower creep ductility than Sn-37Pb
Sn-Ag-Cu	comparatively smallest	20-55%	comparatively strongest	softening (15-20%)	greater creep resistance	extremely sensitive to stress

Source: William J. Plumbridge, The Solder Programme at the Open University Materials, Engineering Department: An Update, 2001 (http://technology.open.ac.uk/materials/mat-hp.html)

* At room temperature and at 75°C; subjected to strain controlled cycling.

** Between -50°C and 130°C; times to rupture examined up to several thousand hours.

*** At 75°C with a strain rate of $10^{-6}s^{-1}$.

Table F.3.4: Tensile and Creep Behavior of Two Sn-Ag-Cu Alloys in the Rapidly Cooled, As-Cast State, Summary Table

Alloy Composition	Tensile Strength* (Strain rate: 10^{-3}/s; 348K)	Creep Resistance**	Time to Rupture (Stress component: approx. 14)
Sn-3Ag-0.5Cu	higher than Sn-3.5Ag (by 20%); double Sn-0.5Cu	better than Sn-3.5Ag	similar to Sn-3.8Ag-0.7Cu; superior than Sn-3.5Ag (x 20)
Sn-3.8Ag-0.7Cu	decreases (with increasing temperature & decreasing strain rate)	better than Sn-3.5Ag	–

Source: Yoshiharu Kariya and William J. Plumbridge, "Mechanical Properties of Sn-3.0mass%Ag-0.5%mass%Cu Alloy", Materials Engineering Department, The Open University, U.K.

* Tensile tests ranged between 263K and 398K.

** Constant load creep tests were carried out at 348K.

Table F.3.5: Tin-Silver-Copper Solder Performance Compared with Sn-Pb, Summary Table

Alloy Family	Sn-Pb	Sn-Ag-Cu
Solder Paste Alloy Composition	Sn-37Pb	Sn-3.5Ag-0.5Cu
Ultimate Tensile Strength	–	slighter lower than Sn-37Pb
Yield Strength	–	slighter lower than Sn-37Pb
Creep Performance	–	superior to Sn-37Pb
Wetting Properties	comparable	comparable
Viscosity (Static & Dynamic)	similar	similar
Tack	similar	similar
Solderability	similar	similar
Reflow Characteristics	similar	similar
Print life	–	longer than Sn-37Pb

Source: Quan Sheng, Charles Bradshaw, Sandy Kwiatek, "Properties of Lead Free Alloy and Performance Properties of Lead Free No-Clean Solder Paste", OMG Americas, 2002

Table F.3.6: Creep Behavior and Wettability of Three Solder Alloys, Summary Table

Alloy Family	Alloy Composition	Melting Temperature (ºC)	Creep / Fatigue	Wettability
Sn-Pb	Sn-37Pb	183	–	–
Sn-Cu	99.3Sn-0.7Cu	227	superior than Sn-Pb	inferior copper wetting (compared with eutectic Sn-Pb)
Sn-Ag-Cu	95.5Sn-4.0Ag-0.5Cu	217-219	–	inferior copper wetting (compared with eutectic Sn-Pb)

Source: Angela Grusd and Chris Jorgensen. "Lead-FREE Alloys: Fitting the Square Peg in the Square Hole", Circuitree, September 1999.

Table F.3.7: Performance of Lead-free Alloys, Summary Table

Alloy Family	Alloy Composition	Melting Range (ºC)	Liquidus Temperature	Wave Soldering	Reflow Soldering	Reliability*
Sn-Cu	Sn-0.7Cu	227	–	optimum	undesirable	–
Sn-Ag-Cu	Sn-3.6Ag-0.9Cu	216-217	~220	–	–	–
	Sn-3.8Ag-0.7Cu	–	~220	–	optimum	similar to / superior than Sn-Pb and Sn-Pb-Ag

Source: Jasbir Bath et al., "Research Update: Lead-Free Solder Alternatives", National Electronics Manufacturing Initiative (NEMI), Circuits Assembly (www.circuitassembly.com), May 2000.

* Reliability testing was carried out from -20 to 125ºC for up to 3,000 cycles; and power cycling from 25 to 110ºC for 5,000 cycles.

Table F.3.8: Lead-Free Alloys during Wave Soldering and in SMT Applications, Summary Table

Alloy Family				
Alloy Composition		Sn-0.7Cu	Sn-3.8-4.0Ag-0.5-0.7Cu (TSC-4)	
Melting Temperature (ºC)		227	217-218	217-218
Wave Soldering	**Dross Production**	–	less than other alloys	less than other alloys
	Wetting Properties	–	good	good
	Joint Reliability	–	superior	superior
SMT Applications	**Joint Reliability**	–	excellent	excellent
	Mechanical Fatigue Resistance	–	excellent	excellent
Comments		used for high temperature lead-free applications	no-clean solder pastes pass Bellcore and IPC specifications	falls under JEIDA recommendation; no-clean solder pastes pass Bellcore and IPC specifications

Source: AIM - Technical Data Sheet (http://www.aimsolder.com/leadfree_tdss.cfm?section=assembly)

Table F.3.9: Thermal and Mechanical Properties of Lead-free Alloys, Summary Table

Property		**Alloy Composition**	
		Sn-0.7Cu	**Sn-4Ag-0.5Cu**
Melting Temperature		227	218
Relative Wetting Properties		poor	weaker & slower than CASTIN®* (lower-Ag content alloy)
Relative Thermal Properties**	**Joint Strength**	poor	good
	Fatigue Resistance	poor	superior
Mechanical Strength - Flex Testing***		failed (cracked solder joints)	passed

Source: Karl Seelig and David Suraski, "Materials and Process Considerations for Lead-Free Electronics Assembly"

* The CASTIN® alloy (Sn-2.5Ag-0.8Cu-0.5Sb), consists of the ternary alloy with the addition of a grain -refining and melting temperature-decreasing dopant.

** Test boards were built using each the alloy in conjunction with 1206 thin film resistors. Thermal shock ranged between -40 to 125ºC for 300, 400 and 500 15-minute cycles.

*** Test boards were built using each alloy in conjunction with 1206 thin film resistors and were subjected to flex testing.

Table F.3.10.a: Mechanical Properties of Lead-free Alloys Compared With Eutectic Sn-37Pb, Summary Table

Physical and Mechanical Properties								
Alloy Family		**Sn-Pb**	**Sn-Cu**	**Sn-Ag-Cu**			**Sn-Ag-Cu-Bi**	
Alloy Composition		Sn-37Pb	Sn-0.7Cu	Sn-3.5Ag-0.7Cu	Sn-3.8Ag-0.7Cu	Sn-4Ag-0.5Cu	Sn-2Ag-0.5Cu-7.5Bi	Sn-3Ag-3Cu-2Bi
Density (g/cm^3)		8.4	7.3	–	7.5	7	8	–
Melting Point (°C)		183	227-240	–	217	217-218	186-212	–
Specific Heat (J/g)		45	–	–	–	–	–	–
CTE (μm per m.°C)		19	–	–	–	–	–	–
Electrical Conductivity (%IACS)*		11.9	13	13	13	–	–	–
Electrical Resistivity (μO-cm)		14.5	10-15	–	13	–	–	10.6
Brinell Hardness (HB) or Vickers Hardness (VHN)		17 (HB)	–	–	15 (HB)	–	–	34.5 (VHN)
Wettability Ratio		95, 91	–	–	–	–	–	97, 96
Tensile Strength (20°C) (N/mm^2 at Strain Rate 0.004 s^{-1})		40	–	48	48	–	–	–
Stress to Rupture	**+/- 5 N/mm^2**	–	4,300	–	–	–	–	–
	+/- 10 N/mm^2	–	1,460	–	–	–	–	–
Joint Shear Strength (N/mm^2 at 0.1 mm/min)	**20°C**	23	23, 20	–	27	–	–	–
	100°C	14	16, 21	–	17	–	–	–
Creep Strength (N/mm^2 at 0.1 mm/min)	**20°C**	3.3	8.6	13	13.0	–	–	–
	100°C	1.0	2.1	5	5.0	–	–	–

Source: NIST and CSM, "Database for Solder Properties with Emphasis on New Lead-free Solders", February 2002, (http://www.boulder.nist.gov/div853/lead%20free/props01.html)

CTE: Coefficient of Thermal Expansion

* 100%IACS = 58.00MS/m

Table F.3.10.b: Mechanical Properties of Sn-0.7Cu, Sn-3.2Ag-0.8Cu and Eutectic Sn-37Pb, Summary Table

Alloy Family	Alloy Composition	Process*	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Uniform Elongation (%)	Total Elongation (%)
Sn-Pb	Sn-37Pb	–	27.2	30.6	3	48
Sn-Cu	Sn-0.7Cu	water quenched (average)	15	19	5.4	20.8
		air cooled	16	22	9.1	41.2
Sn-Ag-Cu	Sn-3.2Ag-0.8Cu	water quenched (average)	28	32	3.4	22.1
		air cooled	20	30	6.2	26.1

Source: NIST and CSM, "Database for Solder Properties with Emphasis on New Lead-free Solders", February 2002, (http://www.boulder.nist.gov/div853/lead%20free/props01.html)

* Two processes were carried out: water quenched and air cooled. Four runs were carried out for the water quenched process and the results were averaged.

Table F.3.10.c: Strength, Ductility and Tensile Properties of Lead-Free Solder Alloys Compared with Eutectic Sn-Pb Alloy, Summary Table

Strength, Ductility and Tensile Properties							
Alloy Family		**Sn-Pb**	**Sn-Cu**	**Sn-Ag-Cu**		**Sn-Ag-Bi-Cu**	
Alloy Composition		Sn-37Pb	Sn-3Cu	Sn-0.5Ag-4Cu	Sn-3Ag-4Cu	Sn-2Ag-7.5Bi-0.5Cu	Sn-2Ag-46Bi-4Cu
Elastic Modulus	**GPa**	15.7	–	–	–	–	–
0.2% Yield Strength	**psi**	3,950	–	3,724	6,276	12,370	9,806
	MPa	27.2	–	25.7	43.3	85.3	67.6
Tensile Strength	**psi**	4,442	6,420	4,312	7,006	13,440	10,070
	MPa	30.6	–	29.7	48.3	92.7	69.4
Relative Elongation (Total)	**%**	48	–	27	22	12	3
Strength Coefficient	**psi**	4,917	–	–	–	–	–
	a	33.9	–	–	–	–	–
Hardening Exponent		0.033	–	–	–	–	–

Source: NIST and CSM, "Database for Solder Properties with Emphasis on New Lead-free Solders", February 2002, (http://www.boulder.nist.gov/div853/lead%20free/props01.html)

Table F.3.10.d: Shear Strengths, Solidus and Liquidus Temperatures, and Wetting Angles, Summary Table

Alloy Family	Alloy Composition	Shear Strength (MPa)*			Temperature		Wetting Angle (degrees)
		Test Temperature			Solidus (ºC)	Liquidus (ºC)	
		22ºC	22ºC	170ºC			
		Cooling Rate**					
		1.5 º/s	10 º/s	10 º/s			
Sn-Pb	Sn-37Pb	–	–	–	183	183	–
	Sn-40Pb	37.4	36.5	4.5	183	188	17
Sn-Cu	Sn-0.7Cu	–	29.8	10.1	227	–	–
Sn-Ag-Cu	Sn-3.6Ag-1Cu	54	67	24.4	217	217.9	–
	Sn-3.8Ag-0.7Cu	–	63.8	25.1	217	–	–
	Sn-4.7Ag-1.7Cu	47	58	21.6	217	–	21

Source: NIST and CSM, "Database for Solder Properties with Emphasis on New Lead-free Solders", February 2002, (http://www.boulder.nist.gov/div853/lead%20free/props01.html)

* Cross-head speed: 0.1 mm/min; gap thickness: 76.2 μm

** Cooling rate in soldering (test) but joints

Table F.3.10.e: Thermal Properties of Candidate Lead-Free Solders, Summary Table

Alloy Family	Alloy Composition	Liquidus Temperature (ºC)	Reflow Temperature (ºC)	Melting Range (ºC)
Sn-Cu	Sn-0.7Cu	227	245-255	227
Sn-Ag-Cu	Sn-3.2Ag-0.5Cu	218	238-248	217-218
	Sn-3.5Ag-0.75Cu	218	238-248	–
	Sn-3.8Ag-0.7Cu	220	238-248	217-220
	Sn-4Ag-0.5Cu	–	–	217-225
	Sn-4Ag-1Cu	220	238-248	217-220
Sn-Ag-Cu-Bi	Sn-3.5Ag-0.7Cu-5Bi	–	–	198-213
	Sn-3.2Ag-1.1Cu-3Bi	240	230-240	–

Source: NIST and CSM, "Database for Solder Properties with Emphasis on New Lead-free Solders", February 2002, (http://www.boulder.nist.gov/div853/lead%20free/props01.html)

Table F.3.10.f: Ternary Sn-Ag-Cu Elastic Properties vs. Temperature, Summary Table

Elastic Property		Test Temperature (°C)				
		-25	25	75	125	160
Yield Stress As-Cast (MPa)	Minimum	41.51	30.13	16.45	13.47	9.63
	Mean	41.645	31.835	20.975	13.635	10.19
	Maximum	41.78	33.54	25.5	13.8	10.75
Yield Stress Aged (MPa)	Minimum	36.77	21.21	16.97	10.71	10.79
	Mean	38.655	21.925	17.005	12.15	11.35
	Maximum	40.54	22.64	17.04	13.59	11.91
Elastic Modulus As-Cast (MPa)	Minimum	2863.6	4956.5	4021.6	2836.8	2217.3
	Mean	3978.3	5357.75	4455.5	3837.25	3309.05
	Maximum	5093	5759	4889.4	4837.7	4400.8
Elastic Modulus Aged (MPa)	Minimum	3415.9	3828.7	3752.6	2742.4	2715.7
	Mean	3495.95	4312.55	4004.8	3336.3	3663.7
	Maximum	3576	4796.4	4257	3930.2	4611.7
Yield Strain As-Cast (MPa)	Minimum	0.011	0.008	0.0053	0.0045	0.0047
	Mean	0.01505	0.00845	0.0062	0.00565	0.0056
	Maximum	0.0191	0.0089	0.0071	0.0068	0.0065
Yield Strain Aged (MPa)	Minimum	0.0165	0.0067	0.0058	0.0054	0.0049
	Mean	0.0178	0.00715	0.00615	0.00555	0.0055
	Maximum	0.0191	0.0076	0.0065	0.0057	0.0061

Source: NIST and CSM, "Database for Solder Properties with Emphasis on New Lead-free Solders", February 2002, (http://www.boulder.nist.gov/div853/lead%20free/props01.html)

F.4 QUALITATIVE PERFORMANCE RESULTS

Alloy Composition*	Comments	Reference
Tin-Copper		
Eutectic Sn-Cu	▸ Has the highest melting temperature. ▸ Is lower in tensile strength and higher in elongation than Sn-Ag and Sn-Pb. ▸ Shear strength is comparable with Sn-Pb. ▸ Creep strength is higher than 100Sn but lower than Sn-Ag-Cu (at 20 and 100°C). ▸ Time to rupture is higher than Sn-Ag-Cu but lower than Sn-40Pb (at 25 and 100°C). ▸ Wetting properties can potentially replace Sn-Pb in wave and reflow processes. ▸ Reflow spreading is better than Sn-Ag but poorer than eutectic Sn-Pb. ▸ Is good for wave soldering. ▸ Wettability (when using an unactivated flux) is lower than Sn-Pb. ▸ Has fairly good fatigue resistance.	Lau et al.
Sn-Cu	▸ Tensile strength drops with increasing temperatures. ▸ Is weaker and more ductile than Sn-Ag-Cu and Sn-Pb. ▸ Creep performance of Sn-0.5Cu is similar to Sn-37Pb and poorer than Sn-Ag-Cu at 75°C.	Plumbridge, William J.
Sn-0.7Cu	▸ Is suitable for high-temperature applications. ▸ Creep/fatigue data is superior to Sn-Pb but inferior to Sn-Ag-*X*.	Grusd, Angela and Chris Jorgensen
Sn-0.7Cu	▸ Is the best choice for wave soldering (along with Sn-3.5Ag). ▸ Is undesirable for reflow applications. ▸ Is similar to eutectic Sn-37Pb for surface-mount use.	Bath et al.
Sn-Cu	▸ High melting temperature prohibits alloy use for temperature-sensitive applications. ▸ Demonstrates poor wetting alloy (as compared with other lead-free solders). ▸ Has a low capillary action to draw it into barrels during PTH technology. ▸ Has poor overall fatigue characteristics. ▸ Lacks the fatigue resistance needed for surface mount. ▸ Cracked during mechanical strength-flex testing indicating a weak joint unable to withstand a wide range of mechanical stresses.	Seelig, Karl and David Suraski
Sn-0.7Cu	▸ Is cost-effective. ▸ Is a good alternative for wave soldering and hand soldering applications. ▸ Has poor wetting.	AIM(a)
Sn-3Cu	▸ Recommended for high-temperature applications only.	AIM(a)
Tin-Silver-Copper		
Sn-3.5Ag-0.9Cu	▸ Tensile strength is higher than eutectic Sn-Pb. ▸ Is higher than Sn-Pb in yield strength, shear strength, impact strength, and creep resistance (alloys near eutectic Sn-Ag-Cu). ▸ Tensile strength, shear strength, and melting temperature increases while elongation decreases (alloys further away from eutectic Sn-Ag-Cu). ▸ Demonstrates the longest time to break in creep tests (Sn-3.5Ag-0.75Cu). ▸ Wettability (when using an unactivated flux) is lower than Sn-Pb but higher than Sn-Cu. ▸ Is a prevailing alternative to lead-containing solder.	Lau et al.
Sn-Ag-Cu	▸ Is difficult to plastically deform and less likely to harden. ▸ Fatigue life is longer than Sn-Pb (sufficient fatigue resistance for use in electronics assembly).	Ochiai et al.
Sn-Ag-Cu	▸ Displays the smallest elongation to failure. ▸ Is stronger than Sn-Cu and Sn-Pb. ▸ Has much greater creep resistance than Sn-37Pb. ▸ Has lower creep ductility than Sn-37Pb. ▸ Potentially the most popular lead-free alloy is Sn-3.8Ag-0.7Cu (patented).	Plumbridge, William J.
Sn-3Ag-0.5Cu	▸ Tensile strength decreases with increasing temperature and decreasing strain rate. ▸ Tensile strength is similar to Sn-3.8Ag-0.7Cu, and superior than Sn-3.5Ag and Sn-0.5Cu (at 10^{-3}/s and 348K). ▸ Creep resistance is comparable to Sn-3.8Ag-0.7Cu and superior to Sn-Ag.	Kariya, Yoshiharu and William J. Plumbridge

Tin-Silver-Copper (contd.)		
Sn-3.5Ag-0.5Cu	▸ Mechanical properties are comparable with Sn-37Pb ▸ Has slightly lower ultimate tensile strength and yield strength than Sn-37Pb. ▸ Creep performance is superior to Sn-37Pb. ▸ Wetting properties is comparable to Sn-37Pb. ▸ Has similar static viscosity, dynamic viscosity, tack, printability, solderability, wide reflow window and reflow characteristics as Sn-37Pb. ▸ Has a larger print life than Sn-37Pb. ▸ Alloy paste is usable in PCB applications.	Sheng et al.
Sn-4Ag-0.5Cu	▸ Is well-suited for high operation temperatures (up to 175ºC). ▸ Joint mechanical stability degrades when the melting point is approached. ▸ Does not wet copper as well as eutectic Sn-Pb when using commercial fluxes.	Grusd, Angela and Chris Jorgensen
Sn-3.9Ag-0.6Cu	▸ Is the preferred choice for reflow soldering. ▸ Demonstrates adequate solderability, yet inferior to Sn-Pb. ▸ In line with the International Tin Research Institute alloy range recommendation, thus qualifying for international standards.	Bath et al.
Sn-3Ag-0.5Cu (LF218™)	▸ Has a low melting point for a lead-free alloy. ▸ Lowest cost alloy from the Sn-Ag-Cu family. ▸ Best wetting Sn-Ag-Cu alloy. ▸ Has excellent solder joint reliability. ▸ Is compatible with all flux types. ▸ Has excellent mechanical fatigue resistance. ▸ Is a virtual drop-in for eutectic Sn-Pb in wave and hand soldering applications. ▸ Produces less dross than other solder alloys, wets well, and provides superior joint strength in wave soldering. ▸ Produces stronger solder joints, has greater mechanical fatigue resistance, and is a virtual drop-in for the eutectic Sn-Pb solder in SMT applications. ▸ In line with JEIDA recommendation. ▸ No-clean solder pastes pass all Bellcore and IPC specifications.	AIM(b)
Sn-3Ag-0.5Cu (LF218™)	▸ In line with JEIDA recommendation. ▸ Lowest cost of pure metals for this alloy.	AIM(a)
Sn-3.8-4Ag-0.5-0.7Cu (TSC-4)	▸ Has a low melting point. ▸ Demonstrates good wetting. ▸ Demonstrates excellent solder joint reliability. ▸ Is compatible with all flux types. ▸ Demonstrates excellent mechanical fatigue resistance. ▸ Is a virtual drop-in for the eutectic Sn-Pb solder in SMT applications. ▸ In line with the NEMI recommendation. ▸ No-clean solder pastes pass all Bellcore and IPC specifications.	AIM(b)
Sn-3.8-4Ag-0.5-0.7Cu (TSC-4)	▸ Demonstrates similar characteristics as CASTIN® and LF218™. ▸ Higher cost of metals than CASTIN® and LF218™. ▸ Presents a potential silver phase change issues.	AIM(a)
Sn-3.5Ag-0.5Cu	▸ Has similar characteristics to Sn-3Ag-0.5Cu ▸ Is slightly higher cost of metals then Sn-3Ag-0.5Cu.	AIM(a)
Sn-4Ag-0.5Cu	▸ Demonstrates good fatigue characteristics (superior thermal fatigue resistance as compared to Sn-Cu). ▸ Has good overall joint strength. ▸ Exhibits some change in grain structure during thermal cycling. ▸ Passed all mechanical strength-flex test requirements. ▸ Sufficient supply of base materials.	Seelig, Karl and David Suraski

Tin-Silver-Copper-Bismuth		
Sn-Ag-Cu-Bi	▸ Surface tension, electrical resistivity, and density are comparable with Sn-Ag, Sn-Ag-Cu and Sn-Ag-Cu-*X*. ▸ Demonstrates superior hardness to Sn-Pb. ▸ Has higher tensile and yield strengths, lower elongation, and a slower creep rate than Sn-Pb. ▸ Wetting behavior is fairly comparable with Sn-37Pb (with 1 or 2% Bi-content). ▸ Outstanding in creep resistance and wetting.	Lau et al.

* Several literature sources cited select characteristics for alloys that differed in composition from that mentioned. Such compositions have been included in parentheses following the appropriate comment.

F.5 REFERENCES

AIM(a): "AIM Lead-Free Soldering Guide: Alloys, Chemistries, Data, Experience, Consultation", (http://www.aimsolder.com/techarticles/AIM%20lead-free%20guide.pdf?section=assembly)

AIM(b): "Technical Data Sheet: Technical Articles: Lead-free Product Data Sheets", (http://www.aimsolder.com/leadfree_tdss.cfm?section=assembly)

Bath, Jasbir, Carol Handwerker, Edwin Bradley, May 2000: "Research Update: Lead-Free Solder Alternatives", *Circuits Assembly, p. 31-40,* www.circuitassembly.com.

Grusd, Angela and Chris Jorgensen, September 1999: "Lead-FREE Alloys: Fitting the Square Peg in the Square Hole", *Circuitree, p. 98-102.*

Kariya ,Yoshiharu and William J. Plumbridge: "Mechanical Properties of Sn-3.0mass%Ag-0.5%mass%Cu Alloy", Materials Engineering Department, The Open University, U.K.

Lau, John H., C.P. Wong, Ning-Cheng Lee, and S.W. Ricky Lee, September 2000: "Electronics Manufacturing With Lead-Free, Halogen Free & Conductive-Adhesive Materials", *McGraw-Hill, Ch. 13: Prevailing Lead-Free Alloys, p. 13.1-13.62.*

National Institute of Standards & Technology (NIST) and Colorado School of Mines (CSM), February 11, 2002 (last updated): "Database for Solder Properties with Emphasis on New Lead-free Solders Release 4.0", *Properties of Lead-Free Solders* (http://www.boulder.nist.gov/div853/lead%20free/props01.html).

Ochiai, Masayuki, Toshiya Akamatsu, Hidefumi Ueda, June 2002: "Reliability of Solder Joints Assembled with Lead-Free Solder", *Fujitsu Science Technology Journal, 38, 1, p. 96-101.*

Plumbridge, William J., 2001: "The Solder Programme at the Open University Materials Engineering Department: An Update, 2001", Materials Engineering Department, The Open University, UK, http://technology.open.ac.uk/materials/mat-hp.html

Quan Sheng, Charles Bradshaw, Sandy Kwiatek, 2002: "Properties of Lead Free Alloy and Performance Properties of Lead Free No-Clean Solder Paste", *Presented at IPC SMEMA Council APEX® 2002 (www.goapex.org).*

Seelig, Karl and David Suraski: "Materials and Process Considerations for Lead-Free Electronics Assembly", AIM: Lead-free Articles, (http://www.aimsolder.com/lead_free.cfm?section=articles#2)

APPENDIX G:
LIFE-CYCLE INVENTORY FUEL DATA

Table G-1. Fuel conversion factors

Fuel	Heat Value (H) (MJ/L)	Reference	Density (D) (kg/L)	Reference
Diesel Fuel	35.875	(1)	0.845	(5)
Heavy fuel oil #6 (residual)	38.579	(1)	0.944	(2)
Light fuel oil #2 (distillate)	36.739	(1)	0.843	(2)
Liquified petroleum gas (LPG)	23.276	(1)	0.542	(2)
Natural Gas	0.034	(3)	7.58×10^{-4}	(4)

References:

1. Davis, S.C. 1999. *Transportation Energy Data Book, Edition 19.* 1999. Center for Transportation Analysis, Oak Ridge National Laboratory, ORNL 6958, Appendix B, Table B1. Oak Ridge, Tennessee, September.
2. Energy Information Administration (EIA) 1999. International Energy Annual 1997. U.S. Department of Energy. DOE/EIA 0219 (97), Washington, DC. April.
3. Based on: Wang, M. 1999. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, Version 1.5. Argonne National Laboratory, University of Chicago.
4. Calculated from: Perry, R.H. and D. Green (Eds.) 1984. Perry's Chemical Engineer's Handbook, 6th Edition, page 9-15, Table 9-13, and p. 9-16, Table 9-14. McGraw-Hill, Inc., New York, NY.
5. www.afdc.doe.gov/pdfs/fueltable.pdf. Took average of values provided for diesel fuel at 60 degrees F.

APPENDIX H:
EXAMPLE TOXICITY CALCULATIONS

APPENDIX H:

EXAMPLE TOXICITY CALCULATION

The following example illustrates how toxicity impacts are calculated. Please refer to Section 3.2.11 of the LFSP report for descriptions of the methodologies for calculating these impacts.

If two toxic chemicals (e.g., toluene and benzo(a)pyrene) are included in a waterborne release to surface water from Process A, impact scores would be calculated for the following impact categories (based on the classification shown in Table 3-1):

- Chronic public health effects, cancer and non-cancer; and,
- Aquatic ecotoxicity.

Despite the output types being waterborne releases, the water eutrophication and water quality impact categories are not applicable here because the chemical properties criteria in Table 3-1 are not met. That is, these chemicals do not contain N or P and are not themselves wastewater streams.

Using chronic public health effects as an example, impact scores are then calculated for each chemical as follows:

Cancer effects:

$$IS_{CHP\text{-}CA:toluene} = HV_{CA:toluene} \times Amt_{TCoutput:toluene}$$

$$IS_{CHP\text{-}CA:benzo(a)pyrene} = HV_{CA:benzo(a)pyrene} \times Amt_{TCoutput:benzo(a)pyrene}$$

Non-cancer effects:

$$IS_{CHP\text{-}NC:toluene} = HV_{NC:toluene} \times Amt_{TCoutput:toluene}$$

$$IS_{CHP\text{-}NC:benzo(a)pyrene} = HV_{NC:benzo(a)pyrene} \times Amt_{TCoutput:benzo(a)pyrene}$$

Table H-1 presents toxicity data for the example chemicals from Appendix E. The hazard values and impact scores are calculated as follows:

Table H-1. Toxicity data used in example calculations

Chemical	Cancer		Chronic non-cancer effects	
	Weight of evidence	**Slope factor (SF) $(mg/kg\text{-}day)^{-1}$**	**Oral (mg/kg-day)**	**Inhalation (mg/m^3)**
Toluene	D, 3	None	100 (NOAEL)	411.1 (NOAEL)
Benzo(a)pyrene	B2, 2A	7.3 (oral) 3.1 (inhalation)	No data	No data

Cancer effects:

The cancer HV for benzo(a)pyrene is calculated as follows:

$$\textbf{Oral: } (HV_{CA\ oral})_i = \frac{1/(oral\ NOAEL_i)}{1/(oral\ NOAEL_{mean})}$$

$HV_{CAoral:benzo(a)pyrene}$ = 7.3 (mg/kg-day)$^{-1}$ ÷ 0.71 (mg/kg-day)$^{-1}$
= 10.3

$$\textbf{Inhalation: } (HV_{CA\ inh})_i = \frac{inhalation\ SF_i}{inhalation\ _{Sfmean}}$$

$HV_{CAinhalation:benzo(a)pyrene}$ = 3.1 (mg/kg-day)$^{-1}$ ÷ 1.7 (mg/kg-day)$^{-1}$
= 1.82

Thus, the cancer HV is 10.3, the greater of the two values. The cancer HV for toluene is zero since it has no slope factor and a WOE classification of D (EPA) and 3 (IARC).

Given a hypothetical waterborne release amount of 0.1 kg of benzo(a)pyrene per functional unit, the impact score for benzo(a)pyrene cancer effects is given by:

$IS_{CHP\text{-}CA,W:benzo(a)pyrene}$ = 10.3 x 0.1
= 1.03 kg cancertox-equivalents of benzo(a)pyrene per functional unit

Toluene's impact score for cancer is zero since its HV is zero.

Non-cancer effects:

Since no data are available for non-cancer effects of benzo(a)pyrene, a default HV of one is assigned, representative of mean toxicity.

The non-cancer HV for toluene is calculated as follows:

$$\textbf{Oral: } (HV_{NC\ oral})_i = \frac{1/(oral\ NOAEL_i)}{1/(oral\ NOAEL_{mean})}$$

= 1/100 mg/kg-day ÷ 1/14.0 mg/kg-day
= 0.140

$$\textbf{Inhalation:} \quad (HV_{NC\ inhalation})_i = \frac{1/(inhal\ NOAEL_i)}{1/(inhal\ NOAEL_{mean})}$$

$$= 1/411.1\ mg/m^3 \div 1/68.7\ mg/m^3$$
$$= 0.167$$

Thus, the non-cancer HV for toluene is 0.167, the greater of the two values.

Given the following hypothetical output amounts:

$Amt_{TC\text{-}O:TOLUENE}$ = 1.3 kg of toluene per functional unit
$Amt_{TC\text{-}O:BENZO(A)PYRENE}$ = 0.1 kg of benzo(a)pyrene per functional unit

The resulting non-cancer impact scores are as follows:

$IS_{CHP\text{-}NC,W:TOLUENE}$ = 0.167 x 1.3
= 0.22 kg non-cancer-equivalents of toluene per functional unit

$IS_{CHP\text{-}NC,W:BENZO(A)PYRENE}$ = 1 x 0.1
= 0.1 kg non-cancer-equivalents of benzo(a)pyrene per functional unit

If these were the only outputs from Process A relevant to chronic public health effects, the total non-cancer impact score for this impact category for Process A would be:

$IS_{CHP\text{-}NC:PROCESS\_A}$ = $IS_{CHP\text{-}NC\text{-}W:TOLUENE} + IS_{CHP\text{-}NC\ \text{-}W:BENZO(A)PYRENE}$
= 0.22 + 0.1
= 0.23 nkg non-cancertox-equivalents per functional unit for Process A.

If the product system Y contained three processes altogether (Processes A, B, and C), and the non-cancer impact scores for Process B and C were 0.5 and 1.0, respectively, impact scores would be added together to yield a total impact score for the product system relevant to chronic public non-cancer health effects:

$IS_{CHP\text{-}NC:PROFILE\_Y}$ = $IS_{CHP\text{-}NC:PROCESS\_A} + IS_{CHP\text{-}NC:PROCESS\_B} + IS_{CHP\text{-}NC:PROCESS\_C}$
= 0.23 + 0.5 + 1.0
= 1.73 kg non-cancertox-equivalents per functional unit for Profile Y.

An environmental profile would then be the sum of all the processes within that profile for each impact category.