Chapter 1

GOAL DEFINITION AND SCOPE

1.1 INTRODUCTION

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

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

1.2 PROJECT BACKGROUND

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

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

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

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

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

1.3.1 Lead-Free Solder Project Purpose

The purpose of the LFSP study is three-fold:

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

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

1.3.2 Previous Research

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

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

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

1.3.3 Need for the Project

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

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

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

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

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

1.3.4 Market Trends

In the year 2000, approximately 48,000 tons (97 million pounds) of lead-based solder were used worldwide (Bernier, 2002). Initiatives in Europe and Japan mandate or require voluntary elimination of lead from electronic products. In Europe, the Restriction of Hazardous Substances (ROHS) in Electrical and Electronic Equipment (2002/95/EC) stipulates restrictions on the use of hazardous substances and will require lead and other selected toxic chemicals in electrical and electronic equipment to be replaced by July, 2006. In Japan, subsequent to takeback (recycling) legislation that took effect in that country in 2001, the Japanese EPA and Ministry of International Trade and Industry (MITI) suggested a voluntary phase-out of lead, with lead levels reduced to half by 2000, and by two-thirds by 2005, along with increased end-of-life (EOL) product recycling.

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

1.3.5 Target Audience and Use of the Study

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

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

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

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

1.4 SUMMARY OF LIFE-CYCLE ASSESSMENT METHODOLOGY

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

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

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

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

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

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

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

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

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

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

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

1.5 PRODUCT SYSTEMS

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

1.5.1 Solder Alternatives

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

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

Table 1-1. Solders selected for evaluation

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

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

1.5.2 Functional Unit

The product systems being evaluated in this project are either lead-based or lead-free solders currently in use within the electronics industry. In an LCA, product systems are evaluated on a functionally equivalent basis. The functional unit normalizes data based on equivalent use to provide a reference for relating process inputs and outputs to the inventory and impact assessment across alternatives.

For this project, the functional unit is a unit volume of solder required to form a viable surface mount or through-hole connection between the PWB and the component (Figure 1-2). The functional unit is based on the understanding that a similar volume of solder is required to fill the space in a solder joint regardless of the type of solder used. The selection of this functional unit is independent of PWB design or configuration, since the number and types of connections formed by the solder would be the same for each alternative. As a result, a volume of one thousand cubic centimeters (cc) of solder was selected for use as the functional unit in the LCA.

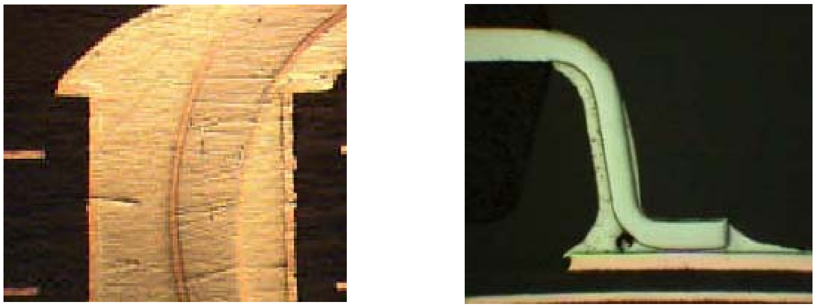


Figure 1-2. Typical Solder Joints for Both Through-hole and Surface Mount Connections

1.6 ASSESSMENT BOUNDARIES

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

1.6.1 Life-Cycle Stages and Unit Processes

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

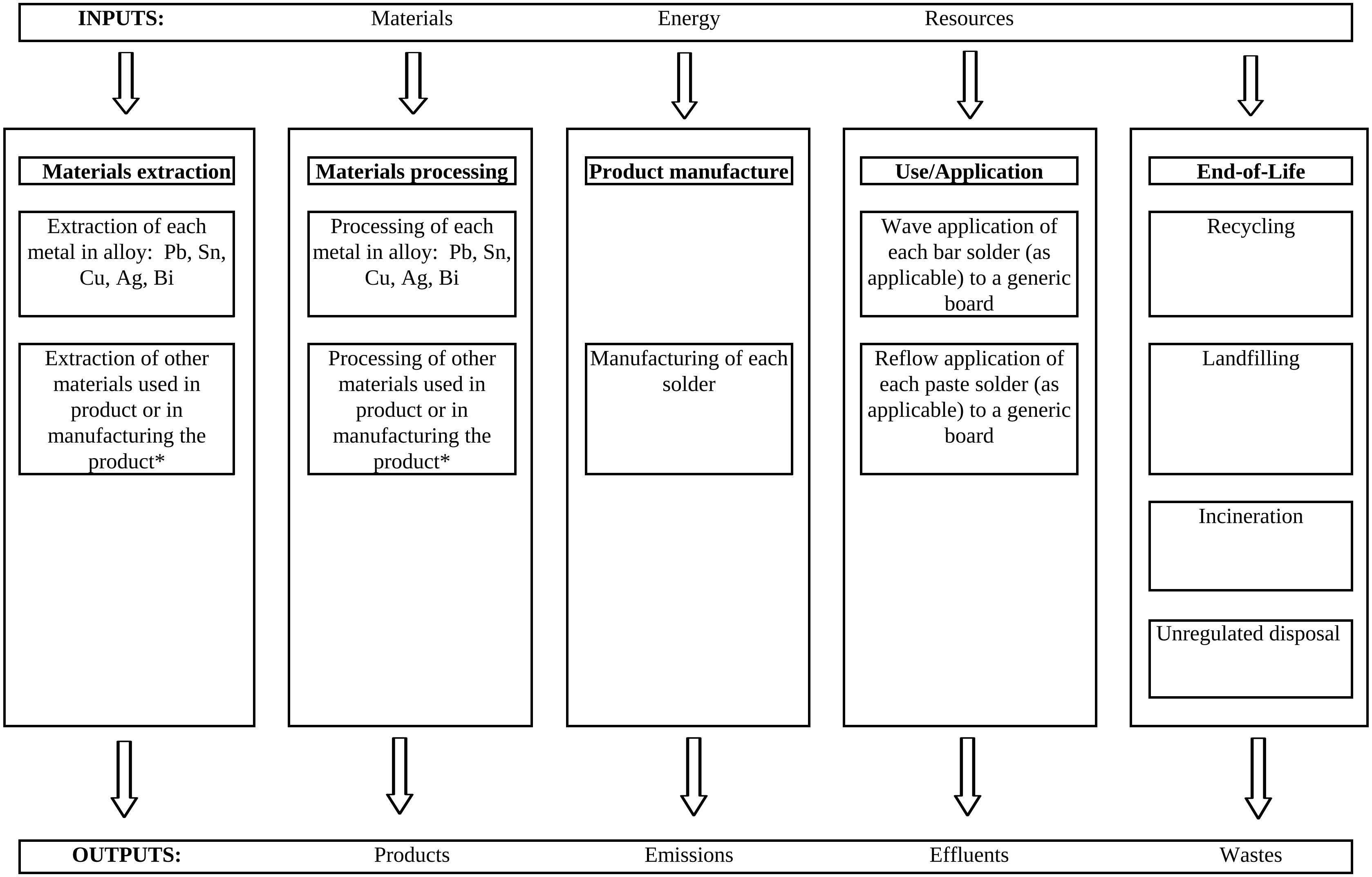
(1) raw materials acquisition;
(2) materials processing;
(3) product manufacture;
(4) product use/application; and
(5) final disposition/EOL.

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

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

1.6.2 Spatial and Temporal Boundaries

Geographic boundaries are used in a LCA to show where impacts are likely to occur for each life-cycle stage. This is important for assessing the impact of such activities as transportation of materials between life-cycle stages. For example, acquisition and processing of materials used in the manufacture of the metals comprising the solder alloys is done throughout the world and is represented by a worldwide database. Product manufacturing also occurs worldwide with data being collected from U.S. and Japanese sources. Similarly, solder application in the use stage is done worldwide; however, given the geographic location of the project researchers, data were only collected from manufacturers in the U.S. The EOL evaluation focuses on solders and electronic products containing solder that reach the end of their lives in the U.S. Due to limited availability of U.S. EOL data (e.g., on recycling), however, EOL data from other countries also were used. For purposes of this study, the geographic boundaries for all life-cycle stages are worldwide; however, several stages are primarily represented by data collected in the U.S.



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

Figure 1-3. Solder Life-Cycle Conceptual Model

1.6.3 General Exclusions

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

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

REFERENCES

Bernier, D. 2002. Personal communication between Dennis Bernier of Kester and Jerry Gleason of Hewlett-Packard, March 25.

CEA (Consumer Electronics Association). 2003. *Annual Electronic Market Data Book 2003*. Consumer Electronics Association.

Curran, M.A. 1996. *Environmental Life-Cycle Assessment*. McGraw-Hill, New York, NY.

DHHS (U.S. Department of Health and Human Services). 1999. *Toxicological Profile for Lead*. Public Health Service, Agency for Toxic Substances and Disease Registry, prepared by Research Triangle Institute, July.

EPA (U.S. Environmental Protection Agency). 2002. *Summary of Lead-Free Solder Performance Based on Existing Data Provided by the Electronics Industry*. Design for the Environment Program, Office of Pollution Prevention and Toxics. Washington, DC. Available at: http://eerc.ra.utk.edu/ccpct/lfsp-docs.html

Fava, J., R. Denison, R. Jones, B. Curran, M. Vigon, B. Selke, S. & J.A. Barnum. 1991. *Technical Framework for Life-Cycle Assessment.* Society of Environmental Toxicology and Chemistry and SETAC Foundation for Environmental Education, Inc. Washington, DC.

ISO (International Standards Organization). 1996. *ISO 14040, Environmental Management - Life-Cycle Assessment Principles and Framework.* TC 2071 SC 5N 77. International Standards Organization, Paris.

NEMI (National Electronics Manufacturing Initiative). 2002. Press Release: “NEMI’s Lead-Free Assembly Project Reports Latest Results at APEX 2002." January 21. Available at: http://www.nemi.org/Newsroom/PR/PR012102b.html, downloaded March 22, 2002.

SETAC (Society of Environmental Toxicology and Chemistry). 1994. *Life-Cycle Assessment Data Quality: A Conceptual Framework*. SETAC and SETAC Foundation for Environmental Education, Inc. Washington, DC.

Van der Wel, H. 2002. E-mail communication between Jack Geibig, of UT, and Has Van der Wel, of Phillips CFT, May 21.

Warburg, N. 2003. “Life Cycle Analysis of Lead-free Solders.” Presentation at IPC Printed Circuits Expo 2003. Anaheim, California. April 1.