WORKSHOP REPORT

SOCIETY OF ENVIRONMENTAL TOXICOLOGY AND CHEMISTRY

A TECHNICAL FRAMEWORK FOR LIFE-CYCLE ASSESSMENTS

August 18-23, 1990

Smugglers Notch, Vermont

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PREFACE

The Society of Environmental Toxicology and Chemistry (SETAC) is pleased to present this SETAC Publication in which can be found information about product, process, and activity life-cycle assessments useful to manufacturers, public interest groups, regulators, consultants, and the general public. This publication is the product of the Life-Cycle Assessment Workshop, the tenth in a series of Pellston-type workshops where experts from around the world have assembled to assess the state of the science of a current environmental issue.

The efforts of the Workshop Steering Committee and staff are gratefully acknowledged, and special thanks go to SETAC Immediate Past-President James Fava who devoted many extra hours to ensure the success of the Workshop. Generous support of numerous corporate, public interest, and governmental groups is also acknowledged.

Rodney Parrish
President, SETAC
August 1990
Smugglers Notch, Vermont
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preface</td>
<td>v</td>
</tr>
<tr>
<td>Foreword</td>
<td>xi</td>
</tr>
<tr>
<td>Executive Summary</td>
<td>xvii</td>
</tr>
<tr>
<td><strong>Chapter 1.0 Introduction</strong></td>
<td>1</td>
</tr>
<tr>
<td>1.1 Overview</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Historical Perspectives on Life-Cycle Inventory Development</td>
<td>3</td>
</tr>
<tr>
<td>1.3 Objectives of the Inventory and Its Application</td>
<td>4</td>
</tr>
<tr>
<td>1.4 Criteria to be Met by Life-Cycle Inventories</td>
<td>6</td>
</tr>
<tr>
<td>1.5 Interpretations and Limitations</td>
<td>7</td>
</tr>
<tr>
<td>1.6 Legal Issues</td>
<td>7</td>
</tr>
<tr>
<td><strong>Chapter 2.0 Framework for a Life-Cycle Inventory</strong></td>
<td>9</td>
</tr>
<tr>
<td>2.1 Scope of an Inventory</td>
<td>9</td>
</tr>
<tr>
<td>2.2 Life-Cycle Inventory Stages</td>
<td>9</td>
</tr>
<tr>
<td>2.3 Construction of a Life-Cycle Inventory Model</td>
<td>11</td>
</tr>
<tr>
<td>2.4 Presentation of Life-Cycle Inventory Results</td>
<td>16</td>
</tr>
<tr>
<td>2.5 Peer Review</td>
<td>25</td>
</tr>
<tr>
<td>2.6 Communication</td>
<td>25</td>
</tr>
<tr>
<td>2.7 Limitations of the Inventory</td>
<td>26</td>
</tr>
<tr>
<td><strong>Chapter 3.0 Raw Materials and Energy</strong></td>
<td>29</td>
</tr>
<tr>
<td>3.1 Overview of the Raw Materials Acquisition System</td>
<td>29</td>
</tr>
<tr>
<td>3.2 Data Analysis</td>
<td>30</td>
</tr>
<tr>
<td>3.3 Reporting</td>
<td>33</td>
</tr>
<tr>
<td>3.4 Recommendations</td>
<td>34</td>
</tr>
<tr>
<td><strong>Chapter 4.0 Manufacturing, Processing, and Formulation</strong></td>
<td>37</td>
</tr>
<tr>
<td>4.1 System Description</td>
<td>37</td>
</tr>
<tr>
<td>4.2 Factors Affecting Output Interpretation</td>
<td>40</td>
</tr>
<tr>
<td>4.3 Data Presentation</td>
<td>42</td>
</tr>
<tr>
<td><strong>Chapter 5.0 Distribution and Transportation</strong></td>
<td>45</td>
</tr>
<tr>
<td>5.1 System Overview</td>
<td>45</td>
</tr>
<tr>
<td>5.2 Components of Transportation and Distribution</td>
<td>47</td>
</tr>
<tr>
<td>5.3 Data Status</td>
<td>53</td>
</tr>
<tr>
<td>5.4 Generic Approaches and Models</td>
<td>54</td>
</tr>
</tbody>
</table>
5.5 Recommendations for Future Development of the Distribution and Transportation Stage ........................................ 55

Chapter 6.0 Use/Re-Use/Maintenance ................................................................. 59
6.1 Boundaries and Scope of Activities ................................................................. 59
6.2 Activities in the Use/Re-Use/Maintenance Phase ........................................... 60
6.3 Data Sources, Methodologies, and Deficiencies ............................................. 63
6.4 Incorporation of End-Use Patterns ................................................................. 70
6.5 Presentation of Inputs, Outputs, and Reporting Format .................................... 71
6.6 Recommendations and Research and Development Needs for Future Life-Cycle Inventory Development ........................................... 72

Chapter 7.0 Recycling ......................................................................................... 75
7.1 Boundaries and Scope of Activities ................................................................. 75
7.2 Activities in the Recycling Stage ..................................................................... 75
7.3 Data Sources, Methodologies, and Deficiencies for Recycling Information .......... 82
7.4 Recommendations and Research and Development Needs ............................ 84

Chapter 8.0 Waste Management ......................................................................... 85
8.1 Overview of Waste Management ................................................................... 85
8.2 Waste Management Systems and Potential Pathways ...................................... 90
8.3 Data Collection and Reporting ...................................................................... 104
8.4 Uncertainties and Research Recommendations ............................................... 112

Chapter 9.0 Research Needs for Life-Cycle Inventories ....................................... 115
9.1 Database Development ................................................................................. 115
9.2 Inventory Methodology Refinement ............................................................... 116

Chapter 10.0 Beyond the Inventory: Setting the Stage for the Environmental Impacts and Improvement Analyses Components of a Life-Cycle Assessment ........................................... 119
10.1 The Bridge from Inventory to Analysis ......................................................... 120
10.2 General Considerations for the Life-Cycle Impact Analysis Component ........ 121
10.3 General Considerations for the Improvement Analysis Component ............. 123
10.4 Environmental Risk Assessment Versus Environmental Analysis ................. 124

Appendix A Glossary .......................................................................................... 125
Appendix B Workshop Participants ..................................................................... 129
Appendix C Life-Cycle Assessment Bibliography and References ........................ 133
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 1</td>
<td>Life-Cycle Assessment Framework Workgroups</td>
<td>xv</td>
</tr>
<tr>
<td>Table 2-1</td>
<td>Sample Data Format Check Sheet</td>
<td>23</td>
</tr>
<tr>
<td>Table 3-1</td>
<td>Typical List of Raw Materials</td>
<td>32</td>
</tr>
<tr>
<td>Table 4-1</td>
<td>Preliminary Data Spreadsheet for Listing Waste Emissions</td>
<td>43</td>
</tr>
<tr>
<td>Table 4-2</td>
<td>Data Spreadsheet for Compiled Data on Product, Primary, and Secondary Packaging</td>
<td>43</td>
</tr>
<tr>
<td>Table 5-1</td>
<td>Common Transportation Modes</td>
<td>47</td>
</tr>
<tr>
<td>Table 5-2</td>
<td>Classification of Environmental Outputs</td>
<td>52</td>
</tr>
<tr>
<td>Table 6-1</td>
<td>Common Data Sources for Components of Use/Re-Use/Maintenance</td>
<td>70</td>
</tr>
<tr>
<td>Table 7-1</td>
<td>Common Data Sources for Components of Recycling</td>
<td>83</td>
</tr>
<tr>
<td>Table 8-1</td>
<td>Categories of Wastes by Source or Character</td>
<td>86</td>
</tr>
<tr>
<td>Table 8-2</td>
<td>Categories of Waste Management Technologies</td>
<td>91</td>
</tr>
<tr>
<td>Table 8-3</td>
<td>Generic Sources of Environmental Releases</td>
<td>92</td>
</tr>
<tr>
<td>Table 8-4</td>
<td>Typical Emissions from Wastewater Treatment</td>
<td>94</td>
</tr>
<tr>
<td>Table 8-5</td>
<td>Potential Pathways from Wastewater Treatment</td>
<td>95</td>
</tr>
<tr>
<td>Table 8-6</td>
<td>Characterization of Controlled and Uncontrolled Emissions to Air</td>
<td>97</td>
</tr>
<tr>
<td>Table 8-7</td>
<td>Sample Airborne Emissions by Generic Production Unit</td>
<td>105</td>
</tr>
<tr>
<td>Table 8-8</td>
<td>Sample Waterborne Emissions by Generic Production Unit</td>
<td>106</td>
</tr>
<tr>
<td>Table 8-9</td>
<td>Solid Waste Loadings by Generic Production Unit</td>
<td>107</td>
</tr>
<tr>
<td>Table 8-10</td>
<td>Sample Format for Generic Production Unit: Environmental Releases, Summary Table</td>
<td>110</td>
</tr>
<tr>
<td>Table 8-11</td>
<td>Total Releases for the Life-Cycle Inventory Component</td>
<td>111</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1</td>
<td>Life-Cycle Inventory</td>
<td>10</td>
</tr>
<tr>
<td>2-2</td>
<td>An Industrial System</td>
<td>11</td>
</tr>
<tr>
<td>2-3</td>
<td>Groups Within an Industrial System</td>
<td>12</td>
</tr>
<tr>
<td>2-4</td>
<td>Inputs and Outputs of a System</td>
<td>13</td>
</tr>
<tr>
<td>2-5</td>
<td>Calculation Sequence</td>
<td>15</td>
</tr>
<tr>
<td>2-6</td>
<td>Simplified Fuel Network</td>
<td>16</td>
</tr>
<tr>
<td>3-1</td>
<td>Primary Raw Material Acquisition System</td>
<td>29</td>
</tr>
<tr>
<td>4-1</td>
<td>Generic Description of a Manufacturing, Processing, and Formulation System</td>
<td>38</td>
</tr>
<tr>
<td>5-1</td>
<td>A Typical Transportation Flow Diagram</td>
<td>48</td>
</tr>
<tr>
<td>5-2</td>
<td>Classification of Carriers</td>
<td>48</td>
</tr>
<tr>
<td>5-3</td>
<td>A Typical Distribution and Transportation Process for Refrigerated Trucks</td>
<td>51</td>
</tr>
<tr>
<td>5-4</td>
<td>A Typical Distribution and Transportation Process for Pipelines</td>
<td>51</td>
</tr>
<tr>
<td>5-5</td>
<td>A Typical Distribution and Transportation Process for Electric Power Transmission Lines</td>
<td>51</td>
</tr>
<tr>
<td>5-6</td>
<td>A Typical Distribution and Transportation Process for a Retail Store and Warehouse</td>
<td>52</td>
</tr>
<tr>
<td>6-1</td>
<td>Boundaries of the Use/Re-Use/Maintenance Stage</td>
<td>60</td>
</tr>
<tr>
<td>6-2</td>
<td>Activities Included in the Use/Re-Use/Maintenance Stage</td>
<td>61</td>
</tr>
<tr>
<td>7-1</td>
<td>Activities Included in Composting and Recycling</td>
<td>76</td>
</tr>
<tr>
<td>7-2</td>
<td>A Closed-Loop Recycling System</td>
<td>77</td>
</tr>
<tr>
<td>7-3</td>
<td>An Open-Loop Recycling System</td>
<td>78</td>
</tr>
<tr>
<td>7-4</td>
<td>Coproduct Recycling</td>
<td>81</td>
</tr>
<tr>
<td>8-1</td>
<td>Generic Pathways of Environmental Releases</td>
<td>89</td>
</tr>
<tr>
<td>8-2</td>
<td>Potential Release Pathways from Wastewater Treatment</td>
<td>93</td>
</tr>
<tr>
<td>8-3</td>
<td>Potential Air Release Pathways</td>
<td>95</td>
</tr>
<tr>
<td>8-4</td>
<td>Potential Release Pathways for Incineration</td>
<td>98</td>
</tr>
<tr>
<td>8-5</td>
<td>Generalized Mass/Energy Flow Model for Land Disposal</td>
<td>100</td>
</tr>
<tr>
<td>8-6</td>
<td>Potential Aquatic Release Pathways</td>
<td>103</td>
</tr>
<tr>
<td>8-7</td>
<td>Data and System Boundaries</td>
<td>109</td>
</tr>
</tbody>
</table>
Recognizing the value of applying life-cycle assessments to environmental problem solving, the Society of Environmental Toxicology and Chemistry (SETAC) organized a workshop, "A Technical Framework for Life-Cycle Assessments," to identify the state of the art in life-cycle assessments and to identify the research needed to enhance the development and use of life-cycle assessment methods. This report is a product of the workshop and can serve as a basis for an initiative to develop the resources needed to conduct the research identified.

This workshop is a continuation of the successful Pellston Workshop Series. Since 1977, nine workshops have been held to address a number of relevant environmental topics. These workshops have been organized and conducted by individuals who are SETAC members. Workshops held to date include:


- **Biotransformation and Fate of Chemicals in the Aquatic Environment.** Held in Pellston, Michigan, August 14-18, 1979. Published by American Society of Microbiology in 1989.

- **Modeling the Fate of Chemicals in the Aquatic Environment.** Held in Pellston, Michigan, August 16-21, 1981. Published by Ann Arbor Sciences in 1982.


Society of Environmental Toxicology and Chemistry

SETAC is a professional society of 2,000 members that was founded in 1979 to provide a forum for individuals and institutions engaged in the study of environmental problems, management and regulation of natural resources, education, research and development, and manufacturing and distribution. It is the only professional society that specifically brings together environmental scientists and engineers from academia, government, industry, and public interest groups to provide research, education, and training in environmental problem solving. SETAC provides a forum through meetings, publications, and workshops for communication among professionals involved in the use, protection, and management of our environment. The goals of SETAC are pursued through such activities as:

- Holding an annual scientific meeting consisting of workshops and scientific paper and poster presentations on topics related to environmental toxicology and chemistry

- Publishing a monthly journal, *Environmental Toxicology and Chemistry*; a bimonthly newsletter, *SETAC News*; and special publications (e.g., *Multispecies Toxicity Testing and Hazard Assessment of Effluents*)

- Organizing and sponsoring chapters to provide a forum for the presentation of scientific data and for the interchange and study of information of more local concern

- Providing advice and counsel to technical and nontechnical people, groups, and institutions about scientific issues through a number of standing and *ad hoc* committees.

This workshop, "A Technical Framework for Life-Cycle Assessments," was organized by SETAC to assess a critical need to enhance our understanding and capabilities through identifying the state of the art in life-cycle assessment and future research needs. SETAC gratefully acknowledges the financial contributions of the workshop sponsors:

American Paper Institute

Aseptic Packaging Council

Battelle

Eastman Kodak Company

Environmental Defense Fund
An Approach to Consensus on a Framework for Life-Cycle Assessments

To develop a consensus on the state of the art and research needs for conducting life-cycle assessments, scientists and engineers representing a broad range of technical expertise were assembled for a one-week workshop. The workshop was held August 18-23, 1990, at Smugglers Notch, Vermont.

The workshop objectives were to clarify definitions and terms associated with life-cycle assessments; to provide a forum for information exchange among researchers from government, industry, academia, and public interest groups; and to agree on a technical framework of key life-cycle assessment components. Additional objectives were to identify research needs to improve life-cycle assessment methods and to develop a strategy for furthering the use of life-cycle assessments in evaluating products, processes, and activities. Workshop participants represented governmental organizations, universities, public interest groups, industry, consultants, and contract research laboratories. Participants were chosen to provide the technical expertise needed to address life-cycle assessment methods.

During the initial phase of the workshop, keynote presentations were made by individuals representing SETAC, U.S. Environmental Protection Agency, Environmental Defense Fund, state governments, and industries. These speakers articulated key issues on the development and use of life-cycle assessments. Additional presentations addressed policy issues, historical perspectives, a European perspective, and a case study. The objective of this initial phase was to establish a common information base.
Prior to the workshop, each participant was asked to prepare a list of issues and thoughts related to improving our understanding and development of life-cycle assessments. These preliminary issue papers were then used as a basis for developing a mutual understanding of life-cycle assessments. Participants were placed in one of six workgroups: Raw Materials Acquisition; Processing, Manufacturing, and Formulation; Distribution and Transportation; Use/Re-Use/Maintenance; Waste Management; and Integration (Table 1). Each workgroup was responsible for developing a framework and identifying research needs within its technical area. The Steering Committee was responsible for synthesizing the findings of the workgroups into a unified report.

Chapter 1 presents an overview of the technical framework for life-cycle assessments and a historical perspective on life-cycle assessments. Chapter 2 provides an overview of the framework for life-cycle inventories. Specific discussions on aspects of the life-cycle inventory component (Component 1) are presented for Raw Materials and Energy (Chapter 3); Manufacturing, Processing, and Formulation (Chapter 4); Distribution and Transportation (Chapter 5); Use/Re-Use/Maintenance (Chapter 6); Recycling (Chapter 7); and Waste Management (Chapter 8). The research needed to improve the inventory component of a life-cycle assessment is discussed in Chapter 9. Research directions and technical considerations necessary to advance the technical framework into Component 2 (Impact Analysis) and Component 3 (Improvement Analysis) are discussed in Chapter 10. Appendix A is a glossary of the technical terms used in this report. Appendix B is a complete list of participants in the workshop, and Appendix C contains references and a bibliography of reports on Life-Cycle Assessment.

It should be emphasized that the majority of this report addresses the life-cycle inventory component of a life-cycle assessment. The workshop report presents a general technical framework from which specific methods and procedures could be developed.
### TABLE 1. LIFE-CYCLE ASSESSMENT FRAMEWORK WORKGROUPS

<table>
<thead>
<tr>
<th>Raw Material Acquisition</th>
<th>Manufacturing, Processing, and Formulation</th>
<th>Distribution and Transportation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mary Ann Curran*</td>
<td>Eric Reiner*</td>
<td>Warren Tyler*</td>
</tr>
<tr>
<td>Richard Storat</td>
<td>James Barnum</td>
<td>Richard Benjamin</td>
</tr>
<tr>
<td>Alan Hershkowitz</td>
<td>David Cornell</td>
<td>Carmine Caruso</td>
</tr>
<tr>
<td>Rodney Parrish</td>
<td>Richard Davis</td>
<td>Sidney J. Everett</td>
</tr>
<tr>
<td>David Scharer</td>
<td>Richard Kimerle</td>
<td>Ahmad Husseini</td>
</tr>
<tr>
<td>Richard Sedlak</td>
<td>Jackie Prince</td>
<td>Masanobu Miyazaki</td>
</tr>
<tr>
<td>Gustav Sundström</td>
<td>Russell Smith</td>
<td>Susan Selke</td>
</tr>
<tr>
<td>Robert Lindenschmidt</td>
<td>Scott Noesen</td>
<td>J. C. Van Weenen</td>
</tr>
<tr>
<td>Greg Eyring</td>
<td>Michael Braungart</td>
<td></td>
</tr>
</tbody>
</table>

TABLE 1. (Continued)

<table>
<thead>
<tr>
<th>Use, Re-use, and Maintenance</th>
<th>Waste Management</th>
<th>Integration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frank Consoli*</td>
<td>Jere Sellers*</td>
<td>Charles Pittinger*</td>
</tr>
<tr>
<td>Diane Boss</td>
<td>Marjorie J. Clarke</td>
<td>Ian Bousted</td>
</tr>
<tr>
<td>Richard Denison</td>
<td>John Gilkerson</td>
<td>Richard Conway</td>
</tr>
<tr>
<td>Anne Robertson</td>
<td>Ellen Harrison</td>
<td>Christine Ervin</td>
</tr>
<tr>
<td>Louise Firth</td>
<td>Susan Mooney</td>
<td>Jaclynn Mullen</td>
</tr>
<tr>
<td>Celeste C. Kuta</td>
<td>James Noble</td>
<td>Gerd Rippen</td>
</tr>
<tr>
<td>Beth Quay</td>
<td>Keith Thomson</td>
<td>Karen Shapiro</td>
</tr>
<tr>
<td></td>
<td>Bruce Vigon</td>
<td>Sharon Stahl</td>
</tr>
<tr>
<td></td>
<td>Mark Stalmans</td>
<td>A. Frances Werner</td>
</tr>
</tbody>
</table>

* Workgroup Chairs.
A TECHNICAL FRAMEWORK FOR LIFE-CYCLE ASSESSMENTS: A SETAC WORKSHOP

Nature and Scope

Environmental professionals, policy makers, and the general public are intensely interested in having the means to look holistically at the environmental consequences associated with the cradle-to-grave life cycle of a process or product. One developing procedure for doing this is termed a "product life-cycle assessment," "ecobalance," or simply a "life-cycle assessment." Although life-cycle assessments have been used in one form or another over the past several decades in Europe, the United States, and a few other countries by industries, governmental agencies, and other organizations, the past several years have seen a growing interest in this environmental analysis tool.

Although life-cycle assessments promise to be a valuable tool in evaluating the environmental consequences of a product, process, or activity, the concept is relatively new and will require a framework for further development. Additional research will enhance our understanding of how to conduct a life-cycle assessment and how to use its results.

The life-cycle assessment is an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment, to assess the impact of those energy and materials uses and releases on the environment, and to evaluate and implement opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process, or activity, encompassing extraction and processing of raw materials, manufacturing, transportation and distribution, use/re-use/maintenance, recycling, and final disposal.

SETAC recognizes the value of life-cycle assessments as one tool to help identify, assess, and solve the environmental concerns associated with products, processes, and activities. As a result of this recognition, SETAC convened a workshop involving 54 scientists and engineers of diverse technical backgrounds representing governmental organizations, universities, industries, public interest groups, consultants, and contract research firms. Also, recognizing that life-cycle assessments have been performed by organizations from several countries, workshop participants were invited from Europe, Japan, and Canada.

Objectives and Context

The charge given to workshop participants was to agree on a technical framework of key life-cycle assessment components. Life-cycle assessments are still in their infancy: the methods for
conducting life-cycle studies must be further developed and refined. The participants, therefore, were also charged with identifying the research needed to improve life-cycle assessment techniques. This workshop report presents a general technical framework from which specific methods and procedures could be developed.

**Main Findings**

Life-cycle assessments have the potential of becoming a powerful tool for helping to reduce the environmental burdens associated with a product, process, or activity. One of the major findings of the workshop was the consensus that complete life-cycle assessments should be composed of three separate but interrelated components. This finding is built on the knowledge that the existing life-cycle assessment efforts have focused primarily on the inventory component.

- **Life-Cycle Inventory**—An objective data-based process of quantifying energy and raw material requirements, air emissions, waterborne effluents, solid waste, and other environmental releases throughout the life cycle of a product, process, or activity.

- **Life-Cycle Impact Analysis**—A technical, quantitative, and/or qualitative process to characterize and assess the effects of the environmental loadings identified in the inventory component. The assessment should address both ecological and human health considerations, as well as such other effects as habitat modification and noise pollution.

- **Life-Cycle Improvement Analysis**—A systematic evaluation of the needs and opportunities to reduce the environmental burden associated with energy and raw materials use and environmental releases throughout the whole life cycle of the product, process, or activity. This analysis may include both quantitative and qualitative measures of improvements, such as changes in product, process, and activity design; raw material use; industrial processing; consumer use; and waste management.

The life-cycle assessment process is not necessarily a linear or stepwise process. Environmental benefits can be realized at each step. For example, the inventory alone may be used to identify opportunities for reducing environmental releases, energy, and material use.

The three components of a life-cycle assessment can provide the information needed to maximize environmental improvements. The interrelationships among the three components are shown below. Currently, most attempts to develop life-cycle assessments have focused on the inventory component. As such, most of the workshop and this report address the life-cycle inventory

```
Inventory
  Life-Cycle Assessment
    Impact Analysis
    Improvement Analysis
```
component of a life-cycle assessment. Considerable research is necessary to develop the impact and improvement analysis components.

**Life-Cycle Inventory**

Participants developed a technical framework for the key phases of a life-cycle inventory. The major life-cycle inventory stages are (1) raw materials acquisition; (2) manufacturing, processing, and formulation; (3) distribution and transportation; (4) use/re-use/maintenance; (5) recycling; and (6) waste management. In general, each stage receives inputs of materials and energy and produces outputs of materials or energy that move to subsequent phases and wastes that are released into the environment. This relationship between the inputs and outputs and the six stages of a life-cycle inventory is shown above.

Investigation into three additional topics will improve the development and use of life-cycle inventories. These relate to the areas of data summation across environmental releases or categories, review of data sources and inventory methods, and data presentation.

**Data Summation Across Environmental Releases or Categories.** One major finding was related to the question of aggregation of individual environmental release quantities. Since individual wastes (pollutants) have different environmental characteristics, the workshop participants agreed that the summation of dissimilar materials in the life-cycle inventory is scientifically unjustified and
represents an incorrect technical approach in the inventory component of a life-cycle assessment. However, it was agreed that some summations are possible; for example, summing the same pollutant emitted from different sources, but in the same form and to the same sector of the environment. Also, some categories of data (i.e., solid waste, energy consumption) can be summed (as long as individual data are also provided), especially if the purpose of the study focuses on that particular criterion.

**Peer and Public Review of Data Sources and Inventory Methods.** Lack of adequate review of the life-cycle inventory methods, the data obtained, and the basis for conclusions was another point of discussion. While confidential or proprietary information must be protected, the workshop concluded that methods and data from a life-cycle inventory must be available for public review if the document is to be used in the public domain in a decision-making context. Peer review and publication of life-cycle inventories are important steps in ensuring their technical and scientific quality. The identification or development of appropriate mechanisms for review and publication was identified as an important research need.

**Data Presentation.** Life-cycle inventories may have different formats depending upon the scope and purpose of the inventory. However, certain general items should be included and recommendations for format should be considered. Presentation of quantitative data should include an identification of data sources and the extent of data completeness and variability. Whereas categorization of data may be employed, aggregation of data should be avoided whenever feasible, and dissimilar data should not be aggregated. It was generally agreed that data should, to the extent possible, be reported for individual outputs rather than aggregates, and the ways to group data were discussed in depth. It was recommended that a review of national and international standards and other possible conventions be undertaken to generate general guidelines for data grouping.

**Research Needs for the Life-Cycle Inventory Component**

Specific research needs to improve the life-cycle inventory methods were identified during the workshop. The identified research needs related to the categories of database development and inventory methodology refinement.

**Database Development**

- Development of data quality standards
- Development of generic databases and guidance on when and how they should be used
- Evaluation of how industry average data should be used in life-cycle inventories
- Development of additional databases.

**Inventory Methodology Refinement**

- Criteria and applications guidance to determine what level of input and output data is meaningful
- Establishment of a standard list of waste sources and pollutants
EXECUTIVE SUMMARY

- Development of generic models

- Development of approaches to allocate inputs and outputs among coproducts

- Development of approaches to allocate energy and environmental releases among incoming waste streams and to all environmental media

- Development of approaches to incorporate data variability

- Development of approaches to take into account sensitivity analysis in life-cycle inventory methodology

- Establishment of a peer review process

- Standardization of life-cycle inventory methods

- Development of effective approaches for communicating life-cycle inventory results.

Recommendations

- A multiyear research initiative is needed to ensure the continued development of effective life-cycle assessment strategies and methods.

- Initial efforts should focus on refining the life-cycle inventory component.

- Additional efforts should include development of approaches to help progress beyond the inventory to the impact and improvement analysis components of a life-cycle assessment.

- Sufficient case studies should be developed to demonstrate the usefulness of life-cycle assessment methodology to a wide range of products, processes, and activities.

- The research initiative should be expanded to include applications of the life-cycle assessment methods to illustrate their use in actually improving products, processes, and activities.

- This new research initiative should build upon and enhance relevant existing pollution prevention research activities.
1.1 OVERVIEW

The life-cycle assessment is an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and material usage and environmental releases, to assess the impact of those energy and material uses and releases on the environment, and to evaluate and implement opportunities to effect environmental improvements. The assessment includes the entire life cycle of the product, process, or activity, encompassing extracting and processing raw materials; manufacturing, transportation, and distribution; use/re-use/maintenance; recycling; and final disposal.

As illustrated below, a complete life-cycle assessment consists of separate, but interrelated components. It should be emphasized that most attempts to develop life-cycle assessments have focused on the inventory component. As such, most of the workshop and this report address the life-cycle inventory component of a life-cycle assessment. Considerable research is needed to develop the impact and improvement analysis components. The workshop participants recognized that the developed life-cycle assessment is broader than that traditionally used.

- **Life-Cycle Inventory**—An objective, data-based process of quantifying energy and raw material requirements, air emissions, waterborne effluents, solid waste, and other environmental releases incurred throughout the life cycle of a product, process, or activity.

- **Life-Cycle Impact Analysis**—A technical, quantitative, and/or qualitative process to characterize and assess the effects of the environmental loadings identified in the inventory component. The assessment should address both ecological and human health considerations, as well as other effects such as habitat modification and noise pollution.
• *Life-Cycle Improvement Analysis*—A systematic evaluation of the needs and opportunities to reduce the environmental burden associated with energy and raw materials use and waste emissions throughout the whole life cycle of a product, process, or activity. This analysis may include both quantitative and qualitative measures of improvements, such as changes in product design, raw material use, industrial processing, consumer use, and waste management.

These three components comprise an integrated approach that, when combined with other appropriate information, can provide the information needed to maximize environmental improvements.

The life-cycle assessment process is not necessarily a linear or stepwise process. Environmental benefits can be realized at each step in the process. For example, the inventory alone may be used to identify opportunities for reducing emissions, energy, and material use. The impact analysis and improvement analysis tools help ensure that these potential reduction strategies are optimized and that improvement programs do not produce unanticipated impacts.

The life-cycle assessment reflects a dynamic and iterative process of evaluation. For example, changes in the material input to a manufacturing process or changes in the process itself—whether the result of the inventory impact reduction assessment or other factors—may trigger the need for an updated inventory. Likewise, new information pertaining to human or environmental exposure and toxicity will trigger the need to update the impact and improvement analyses. This dynamic element underscores that improvements in products and processes are not static accomplishments, rather they continually respond to changes in the system being evaluated and its environment.

The life-cycle inventory component cannot easily accommodate qualitative and/or semi-quantitative information beyond the energy, material, and environmental release data that have been typically included. However, all life-cycle stages generate other potential environmental and nonenvironmental impacts that, although not generally identified as a specific input or output, can still be considered as valuable information in the inventory component of a life-cycle assessment. Characterizing these other possible issues also provides a bridge between the inventory and analyses components. During the inventory component, it could be quite useful to identify these other issues and, to the extent possible, include quantitative and/or existing information about them. Examples of the types of issues that could be considered in the inventory component are listed below and are discussed in greater detail in Chapter 10:

- Ecological Impacts
- Site Selection
- Habitat Alteration
- Community Relations
- Public Perceptions
Good Management Practices

Worker Health Concerns

Public Health and Accident Risk.

1.2 HISTORICAL PERSPECTIVES ON LIFE-CYCLE INVENTORY DEVELOPMENT

Research on various elements of inventories has roots as far back as the 1960s. One of the first publications to report the calculation of cumulative energy requirements for the production of chemical intermediates and products was that of Harold Smith at the World Energy Conference in 1963. This marked the beginning of an interest in calculating the energy requirements of extended production systems.

In the late 1960s a number of workers in various parts of the world undertook global modeling studies. These studies attempted to predict the ways in which population would change and how these changes would affect the demand for raw materials and energy. The results were published in Meadows’ book, *The Limits to Growth*, and in the Club of Rome’s document, *A Blueprint for Survival*. These predictions agreed that increasing raw material and energy demand would lead to such a significant depletion of fossil fuels that exhaustion would be possible in a matter of decades. Furthermore, the waste heat generated would lead to global warming, melting of polar icecaps, and other climatological changes. The somewhat alarming predictions sparked an interest in carrying out more detailed energy calculations on industrial processes.

In the United States, for example, about a dozen major “fuel cycle” studies were performed in the late 1960s and early 1970s to estimate the costs and environmental implications associated with alternative energy sources. Although focusing on energy characteristics, these studies included estimates of gaseous, solid, and liquid emissions. Several major cost minimization studies were also conducted by Resources for the Future and the U.S. Environmental Protection Agency that included materials and energy calculations for such industries as pulp and paper, petroleum refining, and steel. These studies were based on both primary data collection and secondary sources.

Although some skepticism remained about the value of these energy studies, the political climate changed dramatically in the period from 1973 to 1975 when oil shortages occurred, and both the U.S. and British governments commissioned extensive studies of a wide range of industrial systems. Since energy analysis required the construction of detailed mass balances to perform the necessary calculations, the work provided additional data on raw material requirements and on the mass of solid waste emissions.

As memory of the 1970s oil crises faded, interest in energy analysis began to wane, although a number of individuals and organizations in the United States, the United Kingdom, Scandinavia, Switzerland, and Germany continued their activities.

During the 1980s, however, the Green Movement, and especially the formation of Green political parties in Europe, reawakened interest in the subject. The European Commission set up an
Environment Directorate (DG XI), and although much of their work focused on standardizing pollution regulations throughout Europe, they introduced a Liquid Food Container Directive (85/339) in 1985. This charged member countries with monitoring the energy and raw materials consumption, as well as the solid waste generation, in the production and disposal of liquid food containers.

Solid waste also became a worldwide political issue. Pressure from the Green Movement promoted recycling efforts. At the same time, global attention increased on the serious air and water pollution problems and waste management strategies. As a result of these pressures, gaseous, solid, and liquid emissions were routinely added to energy, raw materials, and solid waste considerations, and the last few years have seen a significant increase in research activity in this area.

Concurrent with the widespread development of the life-cycle method in Europe, landmark studies were performed by the Midwest Research Institute (Franklin Associates, Inc.) and Arthur D. Little, Inc. in the mid-1970s. Developed under the title “Resource and Environmental Profile Analysis” (REPA), these early studies became the model for development of the modern life-cycle assessment.

Life-cycle assessment is now becoming an important tool of the technologist and planning analyst. Although the level of interest has fluctuated over the last 20 years, there is no doubt that the Iraqi invasion of Kuwait in 1990 and, once again, the prospect of oil shortages in western industrialized countries, as well as continuing concerns for solid waste disposal capacity and other significant environmental issues, have re-emphasized the continued need for this type of analysis.

1.3 OBJECTIVES OF THE INVENTORY AND ITS APPLICATION

An inventory will provide a quantitative catalog of the inputs (energy and raw materials) and outputs (including environmental releases) for a specific product, process, or activity. Once the inventory has been performed and is deemed as accurate as possible within the definition and limitations of the system, the results can be used in the impact and improvement analyses.

Specific objectives for conducting the inventory include, but are not restricted to, the following:

• To establish a comprehensive baseline of information on a system’s overall resource requirements, energy consumption, and emission loadings for further analysis

• To identify points within the life cycle as a whole, or within a given process, where the greatest reduction in resource requirements and emissions might be achieved

• To compare the system inputs and outputs associated with alternative products, processes, or activities

1See World Wildlife Fund and The Conservation Foundation report dated 1990 on policy issues surrounding life-cycle studies based on a panel discussion among technical and policy specialists.
To help guide the development of new products, processes, or activities toward a net reduction of resource requirements and emissions

To help identify needs for the life-cycle impact analysis

To provide the information needed to conduct an improvement analysis.

These objectives can be further categorized into applications by alternative user groups as depicted below.

**Private Sector Uses**

**Internal Evaluation and Decision Making**

- Compare alternative materials, products, processes, or activities within the organization.

- Compare resource use and release inventory information from other manufacturers.

- Help train personnel responsible for reducing the environmental burdens associated with products, processes, and activities, including product designers and engineers.

- Provide the baseline information needed to carry out other components of the life-cycle assessment.

**External Evaluation and Decision Making**

- Provide information to policy makers, professional organizations, and the general public on resource use and releases, including appropriate disclosure and documentation of findings.

- Help substantiate product statements of quantifiable reductions in energy, raw materials, and environmental releases.

**Public Sector Uses**

**Evaluation and Policymaking**

- Supply information for evaluating existing and prospective policies affecting resource use and releases.

- Develop policies on materials and resource use and environmental releases when the inventory is supplemented with impact assessments.

- Identify gaps in information and knowledge, and help establish research priorities and monitoring requirements on the state and federal levels.
• Help evaluate product statements of quantifiable reductions in energy, raw materials, and environmental releases.

Public Education

• Develop materials to help the public understand resource use and release characteristics associated with products, processes, and activities.

• Help design curricula for training those involved in product, process, and activity design.

Inappropriate Applications of the Inventory

• As discussed further in Chapter 10, the inventory itself does not supply the kind of information needed to evaluate or otherwise characterize environmental impacts.

• Except for statements of quantifiable reductions in energy, raw materials, or environmental releases, claims on policies that imply a net reduction in adverse environmental impact cannot be substantiated with supplemental impact analyses beyond the inventory component.

1.4 CRITERIA TO BE MET BY LIFE-CYCLE INVENTORIES

To be a truly useful technical tool, a life-cycle inventory should meet certain criteria. It is recognized that inventories vary from a screening level to those as complete as technically and practically achievable, so the extent to which various criteria are met can vary, but all the criteria should at least be considered and the extent of analysis clearly stated.

• Scientifically Based—Only scientifically based analysis is used to distinguish between products or to ascertain product life-cycle improvement.

• Quantitative—All energy and material uses are quantified and documented using current databases or measurements with suitable quality control. Uncertainties and assumptions in data and methodology are specified.

• Appropriate Detail—The inventory is carried out to a level of detail commensurate with the purpose of the study, with the availability of data, and with the projected effect of a given parameter on the study conclusions.

• Replicable—The data sources and methodology are sufficiently described or referenced so that comparable results would be obtained from a skilled replication or evidence would exist to explain any deviations.

• Comprehensive—All significant raw material and energy uses and environmental releases are included, or any elements missing because of data availability or cost and time constraints are clearly documented.
• Broadly Applicable—The analysis is sufficiently broad in model conception that the results can be applied to the range of situations expected.

• Consistent—The findings are consistent with those of prior studies, or the reasons for inconsistencies are specified; format is consistent with worldwide practice.

• Peer Reviewed—If the results are to be released to the public or used in a public manner, the report should be peer reviewed, using an accepted protocol.

• Useful—The users of the document can make appropriate decisions concerning the area listed; any limitations to the utility of the report should be clearly listed; and presentations should be clear and understandable.

Meeting these criteria should ensure that a life-cycle inventory report is useful, technically supportable, broadly applicable, and unbiased.

1.5 INTERPRETATIONS AND LIMITATIONS

Interpretation of inventory results is dependent upon such factors as the purpose and context under which the inventory is developed, the extent and reliability of the data, and the intended use of the data. This suggests that care must be used in presenting and communicating the results of a life-cycle inventory.

Inventories can be subject to the following problems in interpretation:

• Those unfamiliar with inventories may misinterpret them as characterizing the actual or potential environmental impact of the products, processes, or activities.

• Public use of inventory data that are incomplete or not presented in context can mislead consumers into believing they are being informed of the total environmental impact or of the most important environmental impacts associated with the product, or that one product is better for the environment than another.

• Readers might infer a higher degree of accuracy to inventories than the quantity or quality of data allows.

• The use of national or aggregated data can mask regional or site-specific variations in energy and material requirements and pollution or waste generated.

1.6 LEGAL ISSUES

It would be prudent to understand all legal liabilities before a life-cycle inventory is undertaken by any group, public or private. The purpose of this section is to emphasize the need for considering legal issues and for seeking professional advice as needed. The issues raised here are examples of some of the major areas.
Life-cycle inventories may:

- Provide input into federal, state, and municipal environmental statutes or court cases that could entail formal, legally binding obligations

- Provide required documentation for marketing claims (truth in advertising)

- Reveal legally reportable information on waste emissions not previously identified

- Inform users of liability issues for both the public and private sectors

- Involve the release of data or information deemed confidential or proprietary.
CHAPTER 2.0

FRAMEWORK FOR A LIFE-CYCLE INVENTORY

2.1 SCOPE OF AN INVENTORY

A life-cycle inventory will provide a catalog and quantification of the energy and material usage and environmental releases associated with a specific product, process, or activity.

To perform a study whose ultimate goal is to evaluate the environmental burden associated with a product, process, or activity, the scope of the study must be clearly defined. The following study components, at a minimum, should be defined:

• The product, processes, or activity to be studied

• Reasons for conducting the study, including the needs and potential applications of pertinent user groups

• How the results of the study will be used by the group performing or sponsoring the study

• The elements of the analysis; for example, “This life-cycle assessment will determine and document the raw material and energy demands of the product being analyzed, including all products or processes contributing to its manufacture and use, and the generation of wastes and coproducts.”

• The elements not addressed; for example, “This study does not address socioeconomic and aesthetic issues.”

2.2 LIFE-CYCLE INVENTORY STAGES

A complete inventory quantifies resource and energy use and environmental releases throughout a product or process life cycle, as illustrated in Figure 2-1. The major life-cycle inventory stages to be considered include the following activities, discussed in Chapters 3 through 8.

Raw Materials Acquisition and Energy. The boundary for the raw material element of the inventory begins with all of the activities needed for the acquisition of a raw material or energy and ends at the first manufacturing or processing stage that refines the raw material. This stage is fully discussed in Chapter 3.
Life-Cycle Inventory

Manufacturing, Processing, and Formulation. The processing step of the inventory component of the life-cycle inventory takes feedstocks or raw materials and converts them to final products. A complete discussion of this stage of the inventory is given in Chapter 4.

Distribution and Transportation. These are features of virtually every stage in a product life cycle. A common attribute of both distribution and transportation is that, although they may involve a change in the location or physical configuration of a product, they do not involve a transformation of materials. Transportation is the movement of materials or energy between operations at different locations and can occur at any stage in the life cycle. Distribution is the transfer of the manufactured product from its final manufacturer to its ultimate end user. Chapter 5 contains a complete description of Transportation and Distribution.

Use/Re-Use/Maintenance. The boundary for this stage of the life cycle begins after the distribution of products or materials and ends at the point at which those products or materials are discarded and enter a waste management system. The detailed discussion of the use/re-use/maintenance stage is presented in Chapter 6.

Recycle. The recycling stage encompasses all activities necessary to take material out of the waste management system and deliver it to the manufacturing/processing stage. Recycling activities are discussed in Chapter 7.

Waste Management. Waste streams are generated at each phase of the life cycle. Waste is any material released to any environmental component—air, water, or land. Waste management systems
include any mechanisms for treating or handling waste prior to its release to the environment. The waste management stage is described in Chapter 8.

Each stage of the life-cycle inventory receives *inputs* of materials and energy and produces *outputs* of materials to a subsequent stage, and wastes may or may not be discharged to the environment. Energy sources may include natural gas, petroleum, coal, nuclear, hydroelectric, solar, wind, and wood. Chapter 3 provides the technical framework for quantifying data on energy use throughout the life cycle. Waste from each life-cycle stage is defined as material generally considered to have zero beneficial use and includes routine emissions from waste management systems, uncontrolled emissions, and accidental releases. Chapter 8 describes the technical framework for identifying and quantifying these wastes as part of the life-cycle inventory component.

### 2.3 CONSTRUCTION OF A LIFE-CYCLE INVENTORY MODEL

#### 2.3.1 The Systemic Basis of Industry

The type of analysis used to develop the inventory of inputs and outputs is concerned with the *systems* that produce products, rather than the products themselves. In this context, a system is defined as the collection of operations that together perform some defined function.

Diagrammatically, any industrial system can be represented by a system boundary that encloses all the operations of interest (Figure 2-2). The region surrounding this boundary is known as the system environment, which acts as the source of all inputs to the system and a recipient for all outputs from the system. These definitions are identical to those used in thermodynamics.

The sign convention used in thermodynamics can also be used for systems analysis. Flows of materials and energy across the system boundary and *into* the system are regarded as positive. Conversely, flows of energy and materials across the boundary and *out of* the system are negative. If the definition of system function and the sign conventions are followed rigorously, then mass and energy balances are simple to establish. Errors are easily made, however, if the definitions are loosely applied.

![Figure 2-2. An Industrial System](image-url)
The important feature of this general definition is that any group of operations that performs a defined function can be treated as a system, so there is no such thing as a “correct” system. One of the problems that arises when attempting to interpret data from published literature is understanding clearly the precise limits of the system that is being described. Of crucial importance in the analysis is defining the system with sufficient precision that it is unambiguous.

2.3.2 Defining a System

The formal definition of a system requires that its function be defined precisely. In practice, industrial systems are usually defined by specifying the nature of the input and output materials and, where necessary, indicating the processing route to be followed when more than one route is practiced. In the type of analysis used to construct life-cycle inventories, the global system is defined such that the inputs are all raw materials taken from the environment and the outputs are waste materials released back into the environment. At some stage within the system these materials will exist in some useful form; this is the product or service delivered to the consumer.

Within the overall system, shown by the broken line in Figure 2-3, three main groups of operations can be identified:

1. Those operations responsible for the production, use, transportation, and disposal of the product (the main processing sequence)

2. The production of ancillary materials, such as the packaging and machinery needed to process the raw materials that feed into the main processing or production sequence

3. The fuel production industries that supply the energy needed to drive the system.

In all three groups of operations, the material inputs will be raw materials from the environment, and so the operations needed to extract these materials from the environment must be included within the system boundary.

![Figure 2-3. Groups within an industrial system](image-url)
2.3.3 Evaluating the Performance of a System

To describe the performance of a system, the overall system must be divided into a series of subsystems linked to each other by balanced material flows. The systems are broken down to a level of detail such that each subsystem corresponds to some physical operation for which input and output data are available. If the breakdown is insufficiently detailed, then the data will be unavailable. If the breakdown is too detailed, then some of the subsystems will have to be combined because input-output information is not available for the degree of analysis specified.

Initially, the production sequences for the ancillary materials, which are essentially side-chains feeding into the main production sequence, are also traced back to raw materials in the environment. Often it is tempting to omit some of these side-chains, especially when the demand for the final product of the side-chain is small. However, it is unwise to neglect any operation until it can be established quantitatively that its contribution to overall system performance is negligible.

Once all of the component subsystems have been identified, each can be regarded as a system in its own right and will take in energy and materials and emit solid waste, air pollutants, water pollutants, and other environmental releases in addition to usable products, as shown in Figure 2-4. In addition to the raw materials impacts, the environmental releases associated with the production, use, transportation, and disposal of ancillary materials used in the system should be included within the system boundary.

The subsystem may now be described by obtaining primary data for the materials and energy inputs and for the usable products and waste produced. When this information has been assembled for all subsystems, the performance of the overall system may be calculated by establishing mass balances among all of the subsystems. The total demand for raw materials and fuels and the total output of solid, liquid, and gaseous wastes from the overall system is simply the sum of the inputs and outputs of all the component subsystems.

2.3.4 Elementary Tests to Ensure that the Model is Correct

Industrial systems are physical systems and must, therefore, obey all scientific laws. It is important to check that no violations occur; in particular:

1. Ensure that the law of conservation of mass applies. Although it is used to construct the mass balances within the system, it is worthwhile to recheck the mass balance for every subsystem once it is thought that a satisfactory balance has been achieved.
2. Ensure that the laws of thermodynamics are obeyed. Of special interest are two rules:
   • The reaction energy of any chemical process cannot be less than the standard reaction enthalpy.
   • The efficiency of any energy conversion process (heat-to-work) cannot be greater than the maximum reversible conversion efficiency.

2.3.5 Input Data

As far as possible, data that describe the performance of a subsystem, unique to that subsystem, should be derived from primary sources. Generally, but not always, the manufacturing/processing/converting subsystems and the use/re-use/maintenance subsystems are unique to the system being studied. Where secondary, published data are used, the data sources should be clearly referenced, any inherent limitations in the data should be clearly identified, and where uncertainty exists about the accuracy of data, appropriate sensitivity analyses should be performed. (See Section 2.4.1 and Chapter 9 for further discussions of data sources.)

Plants frequently obtain the required information from site worksheets. It is essential that the operating period chosen is long enough to smooth out any atypical behavior such as machine breakdowns, start-up operations, or changes in material stock levels. On the other hand, the period should not be so long that genuine changes in performance practice are masked. Experience indicates that the performance over a 12-month period, which usually coincides with the company's accounting period, is best.

It is usually impossible to determine the accuracy of the data supplied by a plant operator. With practice, however, it is possible to conduct two elementary checks:

   • If data are repeatedly obtained from the same source, such as annual reports, then it is possible to identify significant anomalies.

   • If the same data are being obtained from a number of different facilities, then it is possible to cross-compare different sets of information to identify outliers.

Most facilities will claim that their data are correct to within 5 to 10 percent, although for certain processes greater accuracy can be achieved. Of much greater significance, however, is the actual difference in the performance of different plants. For example, the energy consumption of glass containers produced in Britain varies by 17 percent from the average value; this variation is not an error, but a real physical variation in practice.

Although it is tempting to use industry averages in the calculations, it is wiser to use data for individual firms. The model will therefore contain duplicate information on the same process. In the calculations, individual process data may be used or the average for the group of processes may be used. Thus, at the end of the calculations, information on the actual range of industrial practice will be available.
2.3.6 Calculation Procedure

The calculation procedure is relatively straightforward once the normalized input data for each of the component subsystems are available. The calculations can usually be performed by common spreadsheet software on a personal computer.

For example, Figure 2-5 shows a simple sequence of subsystems 1, 2, and 3 for which normalized energy requirements are $E_1$, $E_2$, and $E_3$. If the mass balance indicates masses $m_1$, $m_2$, $m_3$, and $m_4$, then the total system energy will be $m_4E_3 + m_3E_2 + m_2E_1$. This may now be normalized as energy for unit output from operation 3, using mass flow ($m_4$) as the normalizing parameter.

![Linear Sequences](image)

$E_1, E_2, E_3$ are energy per unit output from the subsystems.

Total system energy: $E_s = m_4E_3 + m_3E_2 + m_2E_1$.

Normalized system energy: $E_n = E_s/m_4$.

FIGURE 2-5. CALCULATION SEQUENCE

Although the above discussion relates to energy, the calculation of solid waste and air and water emissions is identical. The raw materials requirements are already determined by the mass balance. During the calculation some care is needed to avoid the occurrence of rounding errors. When intermediate calculations are computer generated, this problem seldom arises.

2.3.7 Networks versus Linear Sequences

Large segments of material processing systems include linear sequences of operations of the type shown by Figure 2-5. However, some segments, such as the simplified sequence shown in Figure 2-6, form nonlinear networks. Sometimes these networks can be converted into pseudolinear sequences, but it must be recognized that such a procedure is an approximation and will introduce errors into the calculation.

The only satisfactory way of dealing with such networks is iteration; that is, initial values are assigned to the operators and the system is calculated. The calculated values are now substituted for the initial values and the system is recalculated. The new values are now substituted and the recalculation performed again. This procedure is repeated until the changes in the recalculated values are equal in accuracy to the input data.

This iterative procedure is an important recent refinement in this type of calculation and has revealed some deficiencies in earlier work. For example, the efficiency for electricity production in
Britain using a pseudolinear system is 30 percent, although that calculated using the iterative procedure is less than 27 percent—a change of 10 percent in the efficiency. The earlier studies underestimated the energy associated with electricity use.

2.3.8 Interdependence of Results

Because the system, as initially defined, essentially determines the characteristics of all the component subsystems, the final results will be characteristic of this specific set of subsystems. If any of these subsystems is changed in any way, then an effect will accrue to all of the other subsystems; that is, the overall mass balances will change. When attempting to use the results, it is important to recognize that a single subsystem cannot be isolated from the system, modified in some way, and re-inserted without affecting the performance of the overall system.

2.4 PRESENTATION OF LIFE-CYCLE INVENTORY RESULTS

Life-cycle inventories may have different formats, depending upon the scope and purpose of the inventory. Any inventory should include a detailed description of the purpose of the study, as well as a statement of the boundaries, specific limitations, and any other basic assumptions.

At present, regardless of intended use, the format used to present results also varies considerably by analyst. Moreover, the organization of these life-cycle inventories, as well as the information and assessments contained within them, often renders these documents inadequate. Indeed, some of these documents might actually serve more to confuse the issue at hand than to clarify it. This occurs for a number of reasons, including

- Inadequate definition of the system to be analyzed
- Limitations in the scope of the inputs and outputs considered
- Haphazard grouping of the data under consideration
- Inadequate explanation of the methodological assumptions used
• Inadequate reporting on data accuracy and availability

• Ambiguous interpretations of the data presented resulting from deficient (or nonexistent) environmental effect characterization and assessment.

2.4.1 Quantitative Data

The collection of data needed for a life-cycle inventory is particularly difficult and complex. Absent or incomplete data, differences in the way data were collected, variations in technologies, and the number, diversity, and potential interactions of individual processing steps contribute to the complexity. It is critical, therefore, to define basic guiding principles for the collection, use, and review of data to be used in a life-cycle inventory.

Presentation of quantitative data should include an identification of data sources and an indication of data completeness and variability. Although categorization of data may be employed, aggregation of data should be avoided wherever feasible, and aggregation of dissimilar data should never be permitted. Whenever possible, actual data should be used rather than estimates or regulatory limits. Use of statistical data such as consumer-based information poses special problems, as discussed in Section 6.4. (Discussion of renewable versus non-renewable data presentation issues is contained in Chapter 3.)

2.4.1.1 Proprietary versus Publicly Available Data

Many life-cycle inventories are conducted for internal use, where confidentiality issues are not relevant. However, those conducted for external use carry a critical issue of proprietary data. Performing complete and thorough inventories often requires use of data considered proprietary by either the manufacturer of the product or the consultant performing the study. As a consequence, current studies often contain insufficient source data or documentation data to permit meaningful external review. This adversely affects the credibility of both the life-cycle inventories and the methodology for performing them.

It is recommended that procedures for peer review of external inventories be developed to allow for maintenance, where necessary, of proprietary information through use of appropriate confidentiality disclosure agreements. Development of generic databases can sometimes reduce reliance on proprietary databases. Therefore, it would be useful to develop, validate, and maintain generic source databases where applicable.

Confidentiality of data is expected to be an important issue. On the one hand, an individual company's trade secrets and competitive technologies must be protected. On the other hand, when collecting data (and later, when reporting the results), claims of confidential business information should not be used to prevent a full and detailed analysis or disclosure of information. This issue has not been resolved. Some form of selective secrecy agreements and/or a certification program for entities performing life-cycle inventories, as well as formalization of peer review procedures, deserve consideration.
2.4.1.2 Data Sources

Sources of publicly available data include, for example:

- U.S. Environmental Protection Agency (EPA) databases—the range of chemical quantities used by site and emissions approximations
- U.S. Department of Energy (DOE) databases—energy usage by industry aggregate
- Country-specific databases
- Open literature, including journals and patents—a wide range of discrete and aggregate data
- Reference books, such as *The Encyclopedia of Chemical Technology*—process flow sheets, some generic process data
- Industry reports, such as SRIs reports on specific industries—economic data on generic processes
- Process simulator databases on chemical thermodynamics
- Specific industry member files—data are usually detailed on process chemical use, coproducts, energy usage.

With general industry data, the user should be aware that the age and specificity of the data can vary and related technologies may have changed.

2.4.1.3 Specificity of Data

The choice between use of average versus case-specific source data is an important issue. Currently no consistency exists regarding the specificity of source data used. The degree of specificity needed is highly dependent upon the scope of the study. Further, no requirements exist regarding discussion of the type of source data used in studies. Because alternative selection of source data can materially affect the life-cycle inventory results, the life-cycle inventory should document in detail the data source and type (e.g., average, worst-case, best-case, case-specific) and include a discussion of its limitations, variability, and impact on the study results. Any life-cycle inventory on a single plant would require more specific data than one dealing with an industrial technology.

Data on specific environmental emissions are preferable in an inventory. For example, data from the manufacturing plants and processes directly related to the material, product, process, or activity under consideration should be used whenever possible. Actual data should be used whenever possible, rather than estimates or regulatory limits. Assumptions and conventions used to gather and report data should be consistent and equitable. Data should be collected at as detailed a level as possible, which allows for a more detailed analysis and reporting mechanism, and all emissions
should be recorded at the same time. If previous aggregation has taken place and the data cannot be further disaggregated, it should be so noted. During the data collection phase, source, age, method of derivation, and any other pertinent data characteristics must be clearly documented. For each type of information, all relevant inputs and outputs should be normalized to a standard unit of output. The data should be normalized to the actual amount of product produced, not the plant capacity (i.e., kilograms of air emissions per metric tons of product actually produced). Data presentation might be further enhanced by the consistent use of metric units.

For internal needs, this type of plant-specific data will be readily available, and in some instances, depending on the use of the life-cycle inventory, only one plant or process needs to be analyzed. For example, a company using an inventory for internal purposes may want to analyze a process for manufacturing product X to inventory the emissions from two optional technologies.

For external uses of an inventory, it may or may not be possible to collect data from every plant manufacturing the product or material being analyzed. Whenever possible, actual or specific data are preferred to industry averages. For example, when the number of plants is limited, an attempt should be made to collect data from all plants and document differences among those plants, with a reporting of ranges. (Some of these relevant differences are discussed in Section 4.4.) The time, cost, complexity, and the range of processes used to make one product may dictate when plant-specific data cannot be used and when it may be necessary to use industry averages.

In those cases where industry averages are applied, the limitations of such a database should be recognized and noted. When using a sample of plants, the guiding principle should be that data are collected from a reasonable and representative number of plants. Ranges (in addition to the average value) must be given for the processes under consideration, and a sensitivity analysis should be performed to assess the range of resources used or pollutants produced by plants in the industry. The data must be clearly documented at this stage to record plant-specific variations, such as different on-site treatment technologies.

2.4.1.4 Age and Frequency of Data

Assuming equal reliability, the most recent data should always be used. If recent data are not available, then the user should consider factors that could help predict the reliability of the existing data. One such factor is the maturity of an industry. In a mature industry, significant changes in emission levels are less likely. If the industry is in a growth phase, then data should be collected more frequently to reflect changing technology. Other changes in plant operations could trigger a need for data updating. It should be recognized that these factors are not absolute since pollution control equipment changes can be independent of industry maturity or plant age.

2.4.1.5 Mainstream versus Fugitive Emissions

Where possible, both mainstream and fugitive emissions should be used. Where data on fugitive emissions do not exist and quantitative estimates cannot be made, some qualitative discussion will be required, and conclusions should explicitly reflect this deficiency.
2.4.1.6 Accidental versus Routine Releases

Both accidental and routine releases should be included. Assuming changes have not been made to the manufacturing process that could affect the likelihood of an accidental release, it may be appropriate to apply a correction factor based on historic accidental release frequency. When appropriate, such a factor should be developed and added to routine emissions. The inclusion of accidental or nonroutine emissions must be quantified with extensive experience in actual operations and pro-rated over production totals. Consideration should be given to the concentration and frequency of accidental releases.

2.4.1.7 Data Gaps

During the data collection process, some gaps of data will likely be encountered. Several situations may occur as a result:

1. Absence of data from one of several producers of a particular product or material. For example, if three of five producers report the data, then only three data points will be averaged to represent the entire process. In certain instances, however, this average value is not indicative of the industry average because of known variations in technologies. In such cases where a variety of technologies exists, it may be more appropriate to assume the missing data is equal to the quantity averaged over only the plants reporting, assign that value to the missing data, and then average the total.

2. Lack of consistency on how many constituents are being recorded (i.e., not every entity may collect the same data on a process). This situation is particularly difficult. The best approach is to document the omission by making explicit that data were missing, not that the value was zero (i.e., during reporting, any total numbers used should be footnoted to explain that actual values may be higher or lower due to missing data).

3. Depending on conventions, data may be reported as nondetectable or as less than a certain value (the detection limit). If nondetectable entries are used, the detection limits must be reported and shall be used as the value. If data are reported as less than a certain value, that particular value will be used. During reporting, any total numbers may be footnoted to indicate that actual values may be lower.

2.4.1.8 Sensitivity Analysis

As noted in Section 2.3, there are few ways of directly validating the primary information from any operator. Moreover, in extended production sequences that may involve hundreds of component subsystems, it may not be possible to obtain detailed primary information on some of the minor inputs in subsystems far removed from the major production sequence; secondary data must therefore be used. It follows that some means is needed to determine whether changes or uncertainties in the data used will significantly affect the final results. Historically, when many of the calculations were performed with a hand calculator, there was an understandable reluctance to carry out any significant analysis of the effect of changing the inputs since it meant extensive and tedious recalculation. However, personal computers make it relatively simple to recalculate a complete system. It has become possible to calculate repeatedly system inputs and outputs using
suspect subsystem data that have been increased or decreased by some predetermined increment. In this way, it quickly becomes obvious how sensitive the overall results are to changes in the input data. This form of empirical sensitivity analysis should be performed for life-cycle inventories; it is essential for suspect primary or secondary data, and desirable for nonsuspect data, to examine the way in which overall system performance might vary with actual physical changes in the system itself. A further discussion of sensitivity analysis for processing and manufacturing data is contained in Chapter 4.

2.4.1.9 Data Grouping

Although it was generally agreed that data should be reported for individual outputs rather than aggregates to the extent possible, the grouping of data remains controversial. "Grouping" means reporting data under subheadings such as "hazardous wastes," "carcinogens," and so forth. The alternative to grouping is to list emissions in an arbitrary order, such as alphabetically or by weight. A substantial number of workshop participants believed that some type of grouping convention is desirable; others believed this should be left to the life-cycle inventory performer to determine.

For example, in the near term, generators of life-cycle inventories could group data according to local material standards. For example, in the United States, federal U.S. EPA classifications exist that could guide the presentation of data; air pollutants could be listed separately, at minimum NESHAPS and criteria discharges. Effluent discharge data that could be listed separately include, at a minimum, Clean Water Act Priority Pollutants, Primary and Secondary Pollutants for Drinking Water Standards, Ambient Water Quality Criteria Pollutants, and so forth. Superfund Amendments and Reauthorization Act 313 discharges could also be listed. Wastes could be grouped as either hazardous (by Resource Conservation and Recovery Act code), nonhazardous industrial, regulated infectious (RCRA, subtitle J), municipal solid waste, or municipal sludge.

Closely tied to this issue is whether reports of emissions should carry some indicator of the potential severity of the environmental effects of a given pollutant as an aid for the analyses components of the life-cycle inventory. Grouping of data under appropriate subheadings is one way to accomplish this. A concern with this method is to avoid the tendency to double-count effluents that appear in more than one category. An alternative method is to list the data in alphabetical or quantity order, but indicate (perhaps in a separate column in the data table) the relevant regulatory classifications.

Another alternative is to include in the data table a column that will describe the environmental relevance for each pollutant. Included could be information such as: Is the pollutant a greenhouse gas? Is it a carcinogen? Does it bioaccumulate? Is it persistent in the environment? This would also make it possible to regroup the data according to environmental impact, so that all those pollutants contributing to acid precipitation, for example, could be examined. It is suggested that a group of experts develop a description of the environmental relevance for all of the pollutants likely to be included in these inventories. (See Waste Management, Chapter 8, for an illustration of report formats.) The majority of workshop participants believed some such indication of potential impact was desirable, but a substantial minority disagreed. Research is needed to address the linkage between the inventory, impact, and improvement analysis components. This is discussed in greater detail in Chapter 10.
A review of national and international regulatory standards to generate an acceptable protocol for grouping data of worldwide usefulness was seen as an important future task by those who favored grouping of data. Other research needs identified by a number of workshop participants include

- Develop a comprehensive list of potential release pathways and waste sources to help ensure that sources not commonly considered, but potentially significant, are included in the analysis.

- Develop a standard list of chemicals and pollutants (possibly grouped by regulatory category) to help ensure that all or the most relevant pollutants are included. Heat and microbial contaminants as well as chemicals should be considered. In addition, some unregulated materials such as CO₂ should be included.

2.4.2 Qualitative Data

Disagreement existed about whether qualitative data should be included in a life-cycle inventory. Many believed it important to include such information to facilitate the life-cycle assessment, whereas others thought this information did not belong in the inventory. Examples of qualitative data that could be included are discussed in Chapter 10.

2.4.3 Format

A variety of data formats could be employed. A suggested format is shown in Table 2-1. Data in this format are shown in general categories, but specific additions and deletions would depend upon the purpose, context, and application of the life-cycle inventory. Downstream use of the inventory should affect the choice of data category to assure maximum benefit of the tool. The investigator should determine the appropriate output unit basis for the investigation (output per 1,000 kg or per use unit, for example); the output unit basis must be actual output, not plant capacity. Data should be reported in Systeme International (SI) units: kg for air, water, and solid waste and MJ for energy. Data should be reported at an accuracy consistent with original sources, although intermediate calculations should avoid rounding errors. It is therefore acceptable that the final data presentation consist of both single numbers and data ranges to accommodate the required degree of accuracy, actual physical variations in plants or technologies, and different significant figures for different items. Uncertainties arising from unavailable data should be clearly identified.

Each entry should consist of one of the following:

- An actual number (i.e., as measured or calculated)

- A detection limit if the data were reported as “nondetectable”

- A number that reflects the upper limit X if the data were reported as less than “X”

- Zero only if really zero

- “Not known” or “not measured.”
TABLE 2-1. SAMPLE DATA FORMAT CHECK SHEET

| Purpose: What is being studied? Why? |
| Scope/Limitations: What are the boundaries of the inventory? Assumptions? |

<table>
<thead>
<tr>
<th>Inputs per ________</th>
<th>Outputs per ________</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw Mat (Kg)</td>
<td>Renew (MJ)</td>
</tr>
</tbody>
</table>

I. Raw Material Acquisition
   (for each raw material from mining/harvesting to delivery at manufacturer's door)
   - Exploration
   - Acquisition Process
   - Maintenance Materials
     (for equipment, pesticides, fertilizer, etc.)
   - Transportation
   - Packaging
   - Waste/Emissions Process

II. Manufacturing, Processing, Formulation
    (for each processing step for all ingredients and packaging up to the point of wholesale/retail sale)
    - Processing Step
    - Waste/Emissions Process
    - List Specific
    - Transportation
    - Packaging
<table>
<thead>
<tr>
<th>III. Distribution and Transportation (from manufacturer to point of use)</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Warehouse</td>
</tr>
<tr>
<td>- Retail/Wholesale</td>
</tr>
<tr>
<td>- Packaging</td>
</tr>
<tr>
<td>- Transportation</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>IV. Use/Re-Use/Maintenance</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Use</td>
<td></td>
</tr>
<tr>
<td>- Storage (e.g., refrigeration)</td>
<td></td>
</tr>
<tr>
<td>- Preparation (e.g., cooking)</td>
<td></td>
</tr>
<tr>
<td>- Operation of equipment</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Maintenance</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>- On-site repair</td>
<td></td>
</tr>
<tr>
<td>- Off-site repair</td>
<td></td>
</tr>
<tr>
<td>- Preventive (e.g., oil change)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Re-Use</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>- On site</td>
<td></td>
</tr>
<tr>
<td>- Retailer/manufacturer</td>
<td></td>
</tr>
<tr>
<td>- Donation/sale</td>
<td></td>
</tr>
<tr>
<td>- Rental</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>V. Recycle/Compost</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>- Collection</td>
<td></td>
</tr>
<tr>
<td>- Transportation</td>
<td></td>
</tr>
<tr>
<td>- Processing</td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 2-1. (Continued)**

<table>
<thead>
<tr>
<th>Inputs per</th>
<th>Outputs per</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw Mat (Kg)</td>
<td>Energy Renew (MJ)</td>
</tr>
</tbody>
</table>

**NOTE:** References should include the source and date of information, time period analyzed, calculation methods and assumptions. *Includes habitat loss, soil erosion, aesthetics, noise.*
Thus, the totals for each constituent for the process will be a total of known constituents. It is recommended that all tables use the heading “Known Amounts.” Further discussion of data presentation is contained in some of the following chapters, especially in Chapter 3 for energy and in Chapter 8 for waste.

2.5 PEER REVIEW

Product life-cycle assessments should be reviewed at the critical stages of model development and before publication. The former usually can be handled by submitting the proposed conceptual model of life-cycle stages with inputs and outputs to technical experts within the client organization.

When used for external purposes, the usefulness of the life-cycle inventory can benefit from a more formal peer review process that incorporates the following criteria:

- Select reviewers who have no stake in the report, are technically qualified, and are motivated by professionalism or honoraria to do a thorough job.

- Use a disinterested party to check that the reviewers’ comments have been addressed adequately in the revised report. If the reviewers are to be listed in the report, they also should be allowed to check that the final report adequately addresses their concerns.

When a life-cycle inventory is used only internally, formal peer review would be optional.

Details of formal review processes can be obtained from the National Research Council, the American Society for Testing and Materials, or a high-quality, refereed journal. Peer review benefits a report by helping to ensure that it meets the criteria listed in Section 2.1, especially that it be technically supportable.

2.6 COMMUNICATION

Since life-cycle inventories can be misinterpreted, the developer of the inventory has a responsibility to inform the reader of its purpose, context, limitations, and implications. Following are some guidelines that could help avoid communication problems.

- Clearly identify in an executive summary all pertinent assumptions and qualifications that may affect interpretation of findings.

- Place the inventory in the proper context by stating that it is one piece of a total life-cycle assessment that also includes life-cycle impact and improvement analyses. By containing only quantities of energy and materials used and pollution generated and released, an inventory is an incomplete characterization of total environmental impact. A description of the whole life-cycle assessment package that includes the impact and improvement analyses would minimize misinterpretation by the reader.

- Educate the reader by communicating as much information relevant to the environmental impact as can reasonably be collected. For example, when tabulating
material releases, list, if possible, whether or not they are regulated under an environmental statute. To the extent that they do not contain proprietary information, all flow charts illustrating sources of releases should be included.

- Consider the use of focus groups to determine how the public might interpret the information.

2.7 LIMITATIONS OF THE INVENTORY

It becomes obvious that each inventory must contain a statement of the limitations of the specific study being conducted. At a minimum, the statement must contain information on those components of the study that were and were not quantified and included and for what reasons (e.g., time, availability of credible data); the base year used in the data set and calculation; the sources for major pieces of data; and any special conventions used consistently, such as the use of worst-case conditions, data ranges, and energy conversion efficiencies. Whether or not the study has been peer reviewed, and whether or not reviewer comments have been incorporated, should be clearly stated, and a list of peer reviewers should be included.

Below is a listing of possible limitations to be documented or questions to be asked concerning life-cycle inventories.

- How broad and deep is the study? Where are the boundaries drawn for ancillary contributing processes?

- What are the trade-offs in terms of practical constraints of this study (e.g., time and money) versus an all-encompassing study?

- What significant limitations affect data in general?

- How much proprietary industry information on processes can be made available to the group performing the life-cycle inventory?
  - Energy consumption for specific process line or individual process components
  - Process waste generation
  - Use of potentially toxic catalysts
  - Process emissions for on-site treatment or fugitive emissions

- Are facilities and processes meeting the minimum standards of regulatory compliance?

- What assumptions affect industry statistics?
  - Energy consumption
  - Water consumption
  - Product output quantities
• How is the life-cycle inventory best made available to those who need it?

• Does changing technology significantly affect timeliness and/or relevance of data?

• What are the limitations concerning accuracy (e.g., degree of significance, rounding, etc.)?

• What is the source of generated information?
  – Industry, government, independent, third party, etc.
  – Primary, secondary, tertiary

• What is the quality of the data (for primary and calculated numbers)?
  – Accuracy and precision—significant figures must reflect reality and be meaningful
  – Source: must be provided with year
  – Conservative estimate versus actual measure
  – Use of actual versus optimal technology mix
  – Statement of assumptions used in extracting data from larger works and data sources
  – Use of peer review or other verification process
  – Use of conventions: energy conversions, standard units (SI versus English), and standard base year for calculations and data

• How did the study address missing data?
  – Make assumptions?
  – Perform survey?
  – Estimate?
  – Personal communication?
CHAPTER 3.0

RAW MATERIALS AND ENERGY

3.1 OVERVIEW OF THE RAW MATERIALS ACQUISITION SYSTEM

3.1.1 Boundaries

The boundary for the primary raw material acquisition system of a life-cycle inventory begins with all activities needed for and resulting from the acquisition of a raw material and ends at the first manufacturing or processing stage that refines that raw material (i.e., up to the gate of the first processing or manufacturing facility). These boundaries are illustrated in Figure 3-1.

Generally, raw material is a primary or secondary (e.g., recovered and/or recycled) feed stock that is used in a manufacturing process. Raw materials produced by the first processing stage (or any subsequent stages) are considered in the processing, manufacturing, and formulation system of an inventory, as described in Chapter 4. Raw materials that are produced as a result of recycling processes are discussed in the use/re-use/maintenance and recycle systems presented in Chapters 6 and 7.

Primary raw materials can be produced by cultivation, harvesting, and replenishment, such as wood or agricultural products, or can be explored and extracted, such as minerals, fossil fuels, air, or water. Handling and transportation steps within the system may prepare or deliver the raw material, but do not refine the raw material.

![Figure 3-1. Primary Raw Material Acquisition System](image)

- Energy
- Materials
- Infrastructure and Capital Equipment

![Figure 3-1. Primary Raw Material Acquisition System](image)

- Exploration and Extraction
- Cultivation, Harvest, and Replenishment
- Handling and Transportation

Outputs
3.1.2 Inputs and Outputs

A number of the inputs to the various stages of the primary raw materials acquisition system can be generalized into three categories:

- **Energy Utilization**—Detailed information on type or mix of the energy sources utilized (e.g., hydroelectric and natural gas) must be included in the database. Electricity should be reported as kilowatt hours, and other energies should be reported in the appropriate units of use, such as liters of fuel oil or cubic meters of gas. If energy usage is converted to an equivalent MJ and is reported in this manner, then the conversion factor must also be included.

  The energy variables include electricity; if possible, electric data should reflect its source as produced in a grid, coproduced, or produced from a specific energy source for the specific manufacturing step. Other energy variables to consider are renewable and nonrenewable fuels used for heat and for conveyance and imported nonelectric energy like steam. Each material and energy input to the manufacturing system must include its tally of inherent energy content, process and precombustion expenditure, and emissions.

- **Materials**—These materials are consumed or used in maintaining the raw material source. Examples include pesticides or growth regulators used in timber or agricultural production and chemicals used to control dust emissions from mineral ore production.

- **Infrastructure and Capital Equipment**—Various types of infrastructure construction and equipment will be required. Examples include roads and buildings, as well as the equipment used to explore, produce, extract, or handle the raw material, such as excavation or harvesting equipment.

A number of outputs generated by the raw materials acquisition system can be generalized into a number of categories. These categories of outputs include air emissions, water effluents, solid wastes, other environmental releases, and habitat changes.

Significant inputs and outputs related to providing the infrastructure and equipment, energy, and materials in the raw materials acquisition system also must be evaluated, as illustrated in Figure 3-1. To make life-cycle inventories more feasible, an approach is needed for classifying these inputs and outputs as significant or nonsignificant so that resources can be directed toward inputs and outputs that are significant.

3.2 DATA ANALYSIS

3.2.1 Acquisition of Raw Materials

It is not yet standard practice to include in life-cycle inventories the outputs from the acquisition of raw materials. These outputs (e.g., oil spills, agricultural runoff, and leaching of mine tailings) may have far more serious impacts on the environment than outputs from subsequent stages in the life cycle of the product. It is therefore desirable that these considerations be made a standard part of future inventories. A problem arises in that some of the outputs associated with the acquisition
of raw materials are difficult to quantify, like aesthetic degradation and destruction of habitat. Nevertheless, it is desirable to characterize these latter types of losses in some way so that they can be accounted for in a subsequent impact analysis.

3.2.2 Use of Raw Materials

Many inventories classify natural resources as either energy resources or nonenergy resources. Although this seems straightforward, such a classification presents a number of ambiguities, some of which are described below.

3.2.2.1 Energy Raw Materials

Primary energy raw materials include natural gas, petroleum, coal, nuclear, and hydroelectric. A distinction is made between renewable (e.g., hydroelectric) and nonrenewable (e.g., fossil) fuels. In current practice, fossil fuel raw material inputs (including the inputs that may later be converted into polymers) are reported as an MJ value to reflect their nonrenewable origin. A correction factor called "precombustion energy" (based on national average data) is applied to account for the energy required to extract the energy raw material. A limited range of environmental outputs (airborne, waterborne, and solid wastes) is listed by using existing DOE and EPA data. When these fuel raw materials are converted to industrial process energy, they cause different environmental outputs. For this reason, and to keep the energy accounts from these different sources separate, the energy inputs and outputs should be cited at each stage of the inventory. Energy furnished from electricity is determined by stating the fuel inputs required to produce the net electrical energy consumed in the various process stages. The distribution of fuel by type is generally determined by using national average electricity input data, but may be product specific in certain life-cycle inventory applications. A specific exception is the energy-intensive steps of aluminum production in which an industry-specific input mix is used that reflects the aluminum industry's heavy reliance on hydroelectric power. Fuel inputs, in MJ equivalents, and environmental outputs are given as mentioned above. The fuel mix used to generate electricity varies greatly from country to country, and sometimes from region to region within a country. Thus, the results of an inventory in one country or region may not be transferable to another. In current practice, all energy consumed in the manufacturing, distribution, transportation, use, disposal, and recycling processes is summed by fuel type and converted into MJ equivalents by using national average data.

In the future, fuel use accounts should be maintained separately by source throughout the inventory, though it seems appropriate also to report an aggregation of renewable and nonrenewable sources. Secondary sources of industrial process energy include thermal energy derived from waste biomass, combustible waste gases, or electricity produced by cogeneration from waste heat. Procedures for crediting energy outputs from secondary sources against primary sources are well established, but it remains controversial how to treat a "waste" product that is subsequently re-used, in the context of evaluating the process that produced that waste. The waste versus coproduct controversy crops up repeatedly at many stages of the inventory, and this relationship needs to be clarified.

3.2.2.2 Nonenergy Raw Materials

The number of raw materials that are typically extracted from the earth to support the production of a very wide range of products is surprisingly small. Based on the production and use
of most containers, packaging, and construction materials, a typical list of raw materials could include those listed in Table 3-1.

**TABLE 3-1. TYPICAL LIST OF RAW MATERIALS**

<table>
<thead>
<tr>
<th>Barites</th>
<th>Cu</th>
<th>Limestone</th>
<th>Phosphate (PO₄)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bauxite</td>
<td>Feldspar</td>
<td>Mg</td>
<td>Rutile (TiO₂)</td>
</tr>
<tr>
<td>Biomass (cotton, com, etc.)</td>
<td>Ferro-manganese</td>
<td>Mn</td>
<td>Sand</td>
</tr>
<tr>
<td>Brine</td>
<td>Gas</td>
<td>Coal</td>
<td>Selenium</td>
</tr>
<tr>
<td>CaSO₄</td>
<td>Iron chromite</td>
<td>NaNO³</td>
<td>Uranium</td>
</tr>
<tr>
<td>Chalk</td>
<td>Lead</td>
<td>Oil</td>
<td>Water</td>
</tr>
<tr>
<td>Clay</td>
<td></td>
<td></td>
<td>Wood</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Zinc</td>
</tr>
</tbody>
</table>

There is no direct way to simplify the inputs of these materials. Attempts to normalize them in terms of known reserves are doomed to failure because the reserves of most materials are commercially sensitive; and, even if known, the reserves will change with time in a way totally unrelated to usage because of the discovery of new deposits, changes in the economics of commodity markets, and so forth.

The use of raw materials is related primarily to conservation arguments rather than to environmental problems; and, in this context, some materials are obviously more strategic than others. For example, sand is in plentiful supply worldwide and is unlikely to become scarce. In contrast, copper ores are available in relatively limited volumes. Therefore, it is possible to rank raw materials in terms of their impact on, for example, extraction energy demand.

Since the use of “renewable” resources is deemed desirable, it is appropriate to maintain accounts of “renewable” and “nonrenewable” resources separately throughout the inventory. A resource is considered renewable if it is being replenished at a rate equal to or greater than the rate of depletion. However, the means by which to “credit” the use of renewable resources in an inventory remains to be clarified (see Section 3.2.3.3). Secondary nonenergy resources include both recycled post-consumer materials and industrial scrap fed back into the same process that produced it. Once again, the procedures for crediting the use of these secondary materials against virgin materials are straightforward, but the question of whether using industrial in-house scrap should be considered recycling or not is controversial. This is another example of the debate over what is the “waste” and what is “coproduct.”
3.2.3 Ambiguities and Limitations

3.2.3.1 Classification Ambiguities

The above classifications of materials are based on the dominant use of the material. Ambiguities arise, however, in cases where the same material can be used both as an energy feedstock and to make products. For instance, petroleum can be used to produce both energy and plastics, and wood can be milled into lumber and burned to produce energy. These ambiguities can lead to biases in inventories. For instance, because of the historical emphasis on petroleum as a nonrenewable energy source, the energy content of the petroleum used to make plastics is added to the actual process energy in figuring the total life-cycle energy consumption. This is perceived by the plastics industry as penalizing the use of plastics compared with use of any other nonrenewable material. To avoid this perceived bias, it may be appropriate to report petroleum feedstocks used for nonenergy products in terms of both mass (or volume) and MJ's. In addition, it may be desirable to calculate process energy, both including and excluding inherent energy.

3.2.3.2 Geographical Limitations

The use of national average data for primary energy sources, consumption, and outputs means that an inventory may not capture actual environmental loadings accurately in a specific region, and will certainly not accurately reflect the situation in a country with a very different primary energy resource mix. Also, this national bias may tend to under- or overstate the environmental inputs or outputs when the raw material is extracted in one country and transported to another.

3.2.3.3 Renewable versus Nonrenewable Resources

The question of how to credit the use of “renewable” resources in an inventory is yet to be clarified. A resource is renewable if its inventory is being replenished at a rate that is equal to or greater than the rate of depletion. In cases where the nation’s inventory of a renewable material is increasing (e.g., wood), it may be appropriate to apply a credit to wood-based products within the inventory framework. However, if reforestation is accompanied by other unaccounted environmental outputs such as habitat dislocation, this must also be considered and discussed. Consideration should also be given to the quality, as well as the quantity, of a renewable resource.

3.3 REPORTING

3.3.1 How to Report the Raw Materials System in an Energy and Material Use and Environmental Release Inventory

The following inputs and/or outputs inherent in the raw material system shall be quantified:

- Acquisition, materials, and processing equipment impacts—those inherent in the production and use of extraction catalysts, growth regulators, pesticides, and equipment

- Air emissions—point and fugitive

1Processing refers to those activities within the raw material system that are necessary to acquire the raw material. An example is the separation of oil and water from well discharge.
• Water effluent—point and non-point
• Solid waste
• Energy
• Other environmental releases.

3.3.2 Data Grouping
A review of national and international regulatory standards is needed to generate a protocol for grouping data that is useful worldwide. This is an important future task. After doing so, data presentation would be enhanced by reporting these in metric units. (See Section 2.4.1.9 for further discussion.)

3.4 RECOMMENDATIONS
Improvements to the state of the art can be made conceptually in two dimensions: sharpen the existing approach through improvements in quality (do the same thing, but do it better) and broaden or change the approach or methodology (try to do something different). Both kinds of improvement are needed.

Inventory Improvements
Boundaries. A fundamental concept that must be accepted by anyone undertaking an inventory is that the raw materials acquisition system not only extends all the way back to the source for each primary raw material, but also extends laterally to include all inputs of energy, materials, and equipment necessary for executing each step of acquisition. Obviously such an analysis soon becomes intractable without some methodology for screening insignificant contributions. It may be necessary to extend the analysis of material inputs beyond the first level to second or even multiple levels to identify all significant contributions. In some cases such secondary contributions are the source of the most crucial impacts of all.

The issue from an analytical point of view is how to define the criteria that will determine what is insignificant and can be discarded or ignored. In the absence of superior logic, an analyst must rely on professional judgement or must establish an arbitrary threshold (e.g., components comprising less than 5 percent of the inputs will be ignored). In addition, such criteria must be applicable to a wide array of different energy and material outputs to the environment. Such a sorting process is essential so that the increased effort of screening more distant activities is balanced by the return of data that are relevant and significant to the prime purpose of the analysis. Research to develop and refine such criteria is needed.

Data Sources and Analysis. A number of areas for improvement were identified in the earlier sections, including the need to document assumptions, validate data, develop minimum standards for data quality, conduct a peer review, and develop a means to peer review inventories containing proprietary data. One specific recommendation is a study to review the adequacy of using national fuel input data for electricity production input. Additional items for the future could include developing a certification procedure and code of ethics for inventory producers.
Reporting. The importance of disaggregating the various energy accounts, as discussed earlier, to maintain clarity of reporting cannot be overemphasized. The energy contents of the raw materials used to manufacture products should be distinguished from the energy consumed in the process. The current methodology of aggregating energy consumption data throughout the inventory process should be continued. However, it should be recognized that energy inputs can be positive as well as negative. Inventory reports also should consider quantifying fossil fuels used as raw material in terms of the amount of raw material consumed, e.g., barrels of oil, cubic meters of natural gas, and so forth. Finally, energy consumed from renewable resources should be reported separately from that consumed from fossil fuel and other nonrenewable energy sources.

The use of internationally accepted terms and units is encouraged to facilitate the widest possible use of inventory results. Taking this concept a little further, a review of international and national regulatory classifications for environmental release categories would help to develop a protocol for grouping data that is useful worldwide.
CHAPTER 4.0

MANUFACTURING, PROCESSING, AND FORMULATION

The manufacturing, processing, and formulation step (hereafter referred to as "processing") of a life-cycle inventory converts feedstocks or raw materials to final products. Processing begins with the initial receipt of raw materials, as defined in the previous section, and includes on-site storage and handling.

The processing step is considered complete when the product is in its final manufactured form and transferred to distribution. Primary packaging and any secondary packaging required to transfer the product to the first distribution site are included in this processing portion of a life-cycle inventory. Further breakdown and repackaging of the product is included in the distribution stage, as described in Chapter 5.

The purpose of this chapter is to detail a useful and practical process that will:

- Identify and, where possible, quantify all relevant processing inputs and outputs. Input requirements include energy and raw materials (including water); outputs include products, coproducts, waste emissions, and energy.

- Provide guidance on a series of critical issues necessary for the completion and presentation of the manufacturing, processing, and formulation stage of the life-cycle inventory.

4.1 SYSTEM DESCRIPTION

4.1.1 Boundaries

System boundaries should be chosen such that "inputs" to the process (e.g., from raw material distribution) and "outputs" (e.g., to product distribution) cross the system boundaries.

Simplified diagrams describing the manufacturing process are shown in Chapter 2 (Figures 2-3 and 2-4). Chapter 2 also describes how subprocesses in the manufacturing system should be handled as linear sequences or networks. In these subprocesses, raw materials are converted to semiproduced materials and eventually to products and coproducts. Figure 4-1 shows another generic description of a manufacturing process. This figure represents the processing of raw materials to make products or packaging, as well as how products are packaged in a box or other similar container, and then overpacked in cartons, pallets, or shrink wrapped. This figure exhibits the total concern of a process analysis, which includes flow from raw materials to a ready-to-ship
RAW TEXT

RM₁ - RMₙ = Each raw material used in the process.
PPR₁ - PPRₙ = Each processing or refining step in the manufacturing of the product.

FIGURE 4-1. GENERIC DESCRIPTION OF A MANUFACTURING, PROCESSING, AND FORMULATION SYSTEM
product. In this case, the product is likely being provided to a consumer. A product for industrial re-use is likely to be packaged only in primary packages such as drums.

Each box in Figure 4-1 can be further evaluated by breaking down the process into unit operations. For example, reaction and formulation can include raw material unpacking, preparation, reaction or formulation, washing, drying, or many more possible process operations in series or parallel. Using this system approach to describe a process will result in consistent evaluation, provided that a consistent approach is taken to define and execute the analysis.

4.1.2 Inputs

Raw materials and energy sources serve as inputs to the processing stage and are discussed in Chapter 3. Semiproduced materials are products from prior process steps. For example, polymer beads being provided to a plastic injection molder after unpacking could represent semiproduced material.

Ancillary materials include grease, cleaning products, and other similar products used to maintain the process, but not specifically intended to enter the product. Trace contaminants below the level of concern for the process output can also be carried as ancillary materials.

Recycled materials are materials that have been produced from a variety of sources. These materials can be consumer disposables, recycled coproducts from other processes, or recycled coproducts from the same process via an internal recycle stream.

4.1.3 Outputs—Products, Coproducts, and Waste

The manufacturing and processing stage results ultimately in the generation of products, coproducts, and wastes. A product is a marketable commodity and the principal outcome of the manufacturing process. Frequently, a single manufacturing process results in the generation of multiple secondary products or coproducts that could be used for alternative purposes. For example, processed meat is the principal product of beef-slaughtering operations. Coproducts include beef tallow (a raw ingredient for soap manufacture), cowhide (leather goods), and bone (bone meal). Wastes are defined as materials that, following treatment, have no market value, intrinsic value, or alternative function and are disposed of to the environment. Coproducts, on the other hand, are retained, as they do have some alternative value or function.

It is important to separate products from coproducts clearly in a life-cycle inventory so that the relative proportion of waste and energy associated with their generation may be properly assigned. For instance, the energy and wastes associated with overall production of beef cattle should be proportioned across all coproducts (meat, leather, tallow, bone meal) to reflect environmental loading costs for the production of all useful commodities.

For purposes of quantifying relevant impacts such as energy, raw materials, and emissions, the convention will be to assign weighted averages allocated on a weight basis. Exceptions to this convention should occur only in those cases in which actual source data clearly distinguish that an impact is caused by one product or coproduct.
Wastes associated with all manufacturing processes are to be considered as post-treatment or controlled emissions. That is, waste streams are evaluated only after processing through all in-line waste treatment and control systems to reflect emissions that are actually discharged to the environment. It is also recognized that some manufacturing emissions escape control devices. Such “fugitive emissions” originating from the manufacturing site must also be considered in the life-cycle inventory to the extent practicable.

It is expected that atmospheric and waterborne emissions, as well as solid wastes generated from manufacturing processes, will comply with all local, state, and federal regulatory requirements for such environmental loadings.

4.1.4 Waste Transformations

On-site waste treatment systems result in a significant transformation of initial waste products. For instance, waterborne organic wastes subjected to biological treatment systems will be transformed to CO₂ and water to a greater or lesser degree as a function of the chemical structure of the wastewater components. Physical and chemical transformations also occur in waste treatment; for instance, a stack scrubber system may convert an airborne waste to a solid waste or waterborne slurry. It is important, therefore, that such transformations be accounted for in a life-cycle inventory. In the case of an air emissions control device, reductions in atmospheric emissions should be balanced by the concomitant generation of solid waste.

Whenever practical, specific data related to the life-cycle inventory study under consideration should be used to quantify the post-treatment transformation products. Biases resulting from the application of industry averages for such transformations should be recognized and reported. The biases could be illustrated by using ranges as well as by reporting industry averages. It is important, however, that only relevant waste treatment technologies be compared because different control devices for the same application result in very different amounts and types of transformation products.

4.2 FACTORS AFFECTING OUTPUT INTERPRETATION

4.2.1 Sensitivity Analysis

The practical limits of time, data availability, and cost, and the range of possible variations in technologies throughout an industry, necessitate that certain assumptions will be used in a life-cycle inventory. It is critical that these assumptions are made explicit. Furthermore, some type of quantitative or qualitative sensitivity analysis should be included in the inventory step. The purpose of this section is to discuss the variables that should be understood and considered in a life-cycle inventory to decide which of these variables should be analyzed in a more detailed sensitivity analysis. Such variables range from basic differences in technologies to other variations in general manufacturing practices, all of which affect the level of inputs and outputs. More specifically, these variables include:

1. The energy variables, as discussed earlier, should be noted, including electricity (which, if possible, should reflect its source). Other energy variables to consider are renewable and nonrenewable fuels used for heat and conveyance, as well as imported nonelectric
energy. Each material and energy input to the manufacturing system must include its tally of inherent energy content, process and precombustion energy expenditure, and releases. The outputs of each manufacturing step include the variables of intended material products, coproducts, and releases.

2. Variations in process release treatment facilities (i.e., age, level of treatment, location) and technologies should be noted if they differ from norms in practice and in different industries.

3. Besides the mass and energy balance variables, other important variables must be considered for each life-cycle inventory. The capacity of the production unit must represent the scope of the analysis. Care must be taken not to compare the processes of differently sized facilities because this could prejudice the results.

4. Production "capacity" must be adjusted to reflect experience, unless specifically stated otherwise. The age of the equipment is pertinent because it affects the amount of releases, energy consumption per unit of production, accident incidence, product yields, and capacity utilization.

5. The frequency and consequence of operational transitions (production sequences) may change total releases and product yields; if so, the effects of transitions must be included.

6. The relationship of production plant life to the total quantity of production should be examined to see if the capital equipment contribution per unit of production is worthy of inclusion in the manufacturing life-cycle inventory and whether it could vary over time.

The analysis gains usefulness when changes in the magnitude of variables are tested for their effect on results and the likelihood of variation is considered. The sensitivity then must reflect not only the magnitude of the change, but also its probability of occurrence. Otherwise, a distorted view of magnitude effects may occur. The more likely variables to consider for sensitivity are yield of raw material to product, scale of operation, and percentage utilization of design capacity.

Finally, the analyst must be careful to test variables in the analysis for sensitivity either singly or in a full or partial factorial design. The influence on results must be judged in light of the magnitude of the change in the variable(s). The ranking of variables by effect must follow a rational plan that the analyst should explain. The analyst needs to be sure the effect calculated, estimated, or seen from a change in variable withstands a test for statistical significance before declaring it significant. Unless otherwise stated, a type-I alpha of 0.05 should be used for determining significance.

4.2.2 Analysis of Data for the Material/Energy Balances

The analysis of data and its manipulation and presentation must conform to the principles of completeness, correctness, and impartiality. No technique should be used that is mathematically unsound or falls outside the body of generally accepted practices.
Material/energy balances must be complete, with no unexplained additions or losses of material or energy. Energy use efficiencies must be stated and used consistently. The reduction of the manufacturing process, with manufacture of secondary materials like packaging, should be represented by blocks with interconnections and relationships included. Return or recycle loops must be identified.

Comparative life-cycle inventories must be conducted to approximately the same degree of system definition. That is, it is unfair to compare two processes that differ in the extent of detail used to describe the manufacturing processes.

Aggregation of data is permitted only when similar data are compiled. It is always preferable to retain the detailed listing used for the compilations. If confidentiality requirements preclude detailing specific data sets, the analyst should develop a means to validate independently such information without compromising confidentiality. The data should not be averaged if they were sought from several sources and only one source produced data on a specific subject while the other sources made no mention of the subject, such as one source reporting HCl emissions from a process while others make no mention.

Inclusion of recycled materials must adhere to a consistent convention if the material is brought into the system defined for the life-cycle inventory manufacturing step. The analyst should be certain the inventory includes the energies and releases connected with the process of recycling the material. For closed-loop recycling, the analyst must be sure the iterations to stability in the mass balance carry the totals for energies consumed and releases made. If sufficient data are available to calculate measures of variance, those variances should be combined by methods of generally accepted practice for estimating total variance.

The methods used to estimate variance should correctly reflect whether steps in manufacturing are in parallel, in series, or in networks. Sufficient data measurements are needed to calculate classical variances. Otherwise, the methods of estimating variability for small data set statistics must be used. Data for releases shown as “not detectable,” meaning that none was seen to the limit of chemical analytical detection, should be included in total aggregates at the level of detection, but not included in calculation of variance.

### 4.3 DATA PRESENTATION

The data supporting a life-cycle inventory for processing can be very complex. To enhance the collection, compilation, and presentation of the data on products and to include all packaging considerations from the input of raw materials to products shipped out at the loading dock, the format in Table 4-1 is suggested. The components are grouped in the categories of raw materials (RM), product processing and refining (PPR), and product packaging and storage (PPS) for each individual manufacturing process. The data are accumulated under the table headings of air emissions, water effluents, and solid wastes by listing specific constituents where possible. The types of specific data that are appropriate to each of the categories in the matrix of Table 4-2 are discussed in Section 2.4. Separate tables for the product stage, primary packaging stage, and secondary packaging stage should be developed.
TABLE 4-1. PRELIMINARY DATA SPREADSHEET FOR LISTING WASTE EMISSIONS

<table>
<thead>
<tr>
<th>Air Emissions (AE)</th>
<th>Effluents (E)</th>
<th>Solid Waste (SW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RM₁</td>
<td>AE₁</td>
<td>E₁</td>
</tr>
<tr>
<td>RM₂</td>
<td>AE₂</td>
<td>E₂</td>
</tr>
<tr>
<td>RMₙ</td>
<td>AEₙ</td>
<td>Eₙ</td>
</tr>
<tr>
<td>PPR₁</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PPR₂</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PPRₙ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PPS₁</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PPS₂</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PPSₙ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In rows RM₁ - RMₙ, record wastes from storage, processing, and handling of each raw material (RM). This may be addressed within the raw materials stage of a life-cycle inventory.

In rows PPR₁ - PPRₙ, record wastes from each product processing and refining (PPR) step.

In rows PPS₁ - PPSₙ, record wastes from each product packaging and storage (PPS) step.

TABLE 4-2. DATA SPREADSHEET FOR COMPILED DATA ON PRODUCT, PRIMARY, AND SECONDARY PACKAGING

<table>
<thead>
<tr>
<th>Emissions</th>
<th>Effluents</th>
<th>Solid Waste</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product</td>
<td>AE₁</td>
<td>E₁</td>
</tr>
<tr>
<td></td>
<td>AE₂</td>
<td>E₂</td>
</tr>
<tr>
<td></td>
<td>AEₙ</td>
<td>Eₙ</td>
</tr>
<tr>
<td>Primary packaging</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Secondary packaging</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
A final tabulation representing the entire system is accumulated from the total of the individual process steps mentioned above. This is shown in Table 4-2. The data reported in each box of the matrix should be reported as either:

- An actual number (i.e., as measured or calculated)
- A detection limit if the data were reported as “nondetectable”
- A number that reflects the upper limit $X$ if the data were reported as “less than $X$”
- Zero only if really zero
- “Not known” or “not measured.”

Thus, the totals for each constituent for the process will be a total of known constituents. It is recommended that all tables use the heading “Known Amounts.”

In presenting the results of a life-cycle inventory, there is a need to communicate the knowledge of those conducting the inventory to others who will apply the inventory to subsequent stages (the impact and improvement analysis components). The analyst should communicate system subtleties and knowledge about the current waste management or control technologies of each processing step, as well as possible future additional control options.
CHAPTER 5.0

DISTRIBUTION AND TRANSPORTATION

5.1 SYSTEM OVERVIEW

5.1.1 Definitions

Distribution and transportation are features of virtually every product life cycle. A life-cycle inventory that does not explicitly consider the inputs and outputs of the distribution and transportation activities is, in all likelihood, methodologically deficient.

An important common attribute of distribution and transportation is that, although they may involve a change in the location or physical configuration of a product, they do not involve a transformation of materials. (In practice, these boundaries are not always sharp: for instance, freezing a truckload of beef *en route* or creating cement in a cement mixer during transport can certainly be considered both transportation and transformation. However, these are exceptions rather than the usual case.)

For the purpose of this document, distribution and transportation have been defined as follows:

- *Transportation*—Movement of materials or energy between operations at different locations.

- *Distribution*—All nontransportation activities carried out to facilitate the transfer of manufactured products from their final manufacturer to their ultimate end user. This includes movement of goods within a warehouse or retailing establishment.

Although these may not be the usual definitions, they were chosen to emphasize the commonalities between activities occurring in various stages of a product life cycle. Understanding these commonalities can benefit the execution and use of life-cycle inventories.

To further explain how these terms are applied, some examples may be helpful. *Transportation* includes moving raw materials from a production facility to a processing facility, moving finished goods from a production facility to a warehouse, moving products from point of sale to point of use, and moving electricity from a generation site to a use site. By arbitrary convention, distribution and transportation are associated with the connections between their respective boxes in flow diagrams. It therefore follows that, if a production facility is defined as a black box system, then transportation does not include moving goods from one part of the production facility to another part of the same facility, whether by conveyor belt, forklift, or any other method.
Consistent with our definition, distribution includes warehousing, wholesaling, retailing, and support activities carried out at these locations, such as inventory control or repackaging. It does not include the production or manufacture of a product at a retail or wholesale facility, such as an in-store bakery operation.

Both distribution and transportation include, where appropriate, environmental controls such as maintaining temperature and humidity. Although the definition used here for transportation explicitly excludes movement of a material within a facility, it should be kept in mind that many of these activities are not fundamentally different from movement between facilities. Therefore, much of the following discussion may apply to those activities as well.

5.1.2 Scope

This chapter addresses issues related to both distribution and transportation activities, as defined above, wherever they may appear in the product life cycle. They are thus not independent from a life-cycle inventory, but integrally tied to many other parts.

In this chapter, the elements of distribution and transportation are identified, boundary conditions are discussed, and typical inputs and outputs are noted. The status and applicability of data and generic models are also addressed. Finally, recommendations for future development and improvement of the distribution and transportation portions of life-cycle inventories are outlined.

5.1.3 Limitations

As discussed in Chapter 2, life-cycle inventories and their interpretation and use carry a number of important limitations. In addition, some specific limitations are noted in this chapter on the distribution and transportation portions of a life-cycle inventory.

First, as noted above, distribution and transportation are not an independent portion of a product life cycle because they are so intimately tied to various other activities. The boundaries of the numerous transportation activities, for instance, are defined by those of the activities with which they connect and depend on analysis of these activities for quantification of the amount and type of material or energy being transported in each transportation segment.

Another area of interaction concerns the quantification of the overall outputs that can be attributed to a transportation segment. For example, if $X$ liters of diesel fuel are used, the outputs properly include those associated with production and delivery of the diesel fuel, as well as its combustion in the truck. The distribution and transportation segments of a life-cycle inventory must rely on the energy component for accurate presentation of those outputs. Thus, in both cases the accuracy of the input and output information provided by the distribution and transportation component of a life-cycle inventory will be affected by the accuracy of other components.

Similarly, this chapter is limited to identifying and discussing the inputs and outputs associated with distribution and transportation. Issues of how to deal with renewable versus nonrenewable fuel sources, effects of emissions, organization of recycling, or treatment of wastes are addressed elsewhere.
5.1.4 Impact and Improvement Analyses

This chapter, as others, focuses on the life-cycle inventory aspects of life-cycle assessments. It is important to keep in mind that impact analysis and ultimately product and process improvement are the desired results of a life-cycle assessment.

Within distribution and transportation operations, therefore, it is important in carrying out a life-cycle assessment to look for opportunities for improvement. Outputs that are likely to have significant environmental impacts can be identified as priorities for assessment. On occasion, the size or nature of outputs can suggest immediate changes in distribution or transportation operations, followed, perhaps, by revision of the life-cycle assessment to document the change in outputs. In other cases, complete redesign of the distribution or transportation operation may be the result.

5.2 COMPONENTS OF TRANSPORTATION AND DISTRIBUTION

5.2.1 Modes of Transportation and Distribution

For each mode of transportation, a transportation measure will be described that, with a given quantity of product, will allow determination of the energy and material required and wastes generated in transporting the product a given distance. Common transportation modes are listed in Table 5-1; a typical transportation flow diagram is shown in Figure 5-1.

Distribution modes include warehousing and its supporting functions, from wholesale through the retail stages of a product's distribution. It includes secondary and tertiary packaging and depackaging, handling, and storage (shelving). The measure for storage requires very specific

<table>
<thead>
<tr>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Railway</td>
</tr>
<tr>
<td>· Diesel</td>
</tr>
<tr>
<td>· Electric</td>
</tr>
<tr>
<td>· Steam (coal)</td>
</tr>
<tr>
<td>Airplane</td>
</tr>
<tr>
<td>Truck</td>
</tr>
<tr>
<td>Barge</td>
</tr>
<tr>
<td>Freighter</td>
</tr>
<tr>
<td>Supertanker</td>
</tr>
<tr>
<td>Pipeline</td>
</tr>
<tr>
<td>Electrical power lines</td>
</tr>
</tbody>
</table>
information about the particular product and emerges from a detailed description of that particular product's distribution scheme.

Control of factors such as temperature, relative humidity, and oxygen concentration (commonly referred to within the distribution industry as "environmental controls") may be a part of either a distribution or a transportation mode. Examples include refrigerated trucks and modified atmosphere storage systems.

For the purpose of identifying possible outputs, three classifications of transportation modes can be distinguished:

- Transportation involving movement of the carrier (e.g., plane, ship, truck)
- Transportation with a fixed carrier (e.g., line, wire, pipe, duct)
- A combination of the above (e.g., a tube-post delivery system).

In the case of a movable carrier, a fixed quantity (batch) of material is transported. In the case of a fixed carrier, the material is transported continuously. The batch carrier may or may not use a means of containment. If a form of containment is part of the carrier, then this is either separable (container truck) or integral (tank truck). The container itself may consist of one or more identical or dissimilar units. Further, the container may or may not be specific to the carrier.

The various types of transportation carriers are indicated in Figure 5-2.
5.2.2 Boundary Conditions

As in all other life-cycle inventory stages, the boundaries of distribution and transportation systems must be explicitly defined. So long as data and systems are properly matched, the choice of boundaries is arbitrary: there are no "right" or "wrong" approaches, just more or less detailed evaluations, consistent with the life-cycle inventory objectives.

Even simple distribution and transportation systems can reasonably incorporate far-reaching boundaries. At its simplest level, a highway transportation system might encompass only trucks; at a higher level, trucks and roadways; at a still higher level trucks, roadways, and truckstops. Each boundary expansion adds richness—and cost—to the analysis.

Boundaries can also be defined in terms of process. The simple truck model might include only those inputs and outputs associated with operating the truck, excluding issues of maintaining the truck (e.g., spare parts) and building the truck (truck factories). In principle, maintenance and building processes have their own associated maintenance and building processes, so that a complete description of a single element of a distribution and transportation activity may incorporate a nearly infinite web of first, second, and still higher level systems.

In this picture, boundaries relevant to the distribution and transportation component of a life-cycle inventory are of three types: life cycle (longitudinal), lateral (breadth), and level (depth). Life-cycle boundaries are those having to do with where distribution and transportation operations occur within and between each of the components, from raw materials to waste management. For example, various materials may be moved within a factory or between factories, or a product may be distributed from a warehouse to a retail establishment.

Lateral boundaries have to do with other products and their life-cycle steps. These boundaries are generally selected as part of defining the scope of the overall life-cycle inventory. More than one principal product may be included to capture interrelationships such as highly integrated or comlinged production steps, including transfers of recycled materials between production steps.

The mainstream of a product life cycle is the first level of the distribution and transportation phase. It can be described generally as the raw materials-manufacturing-distribution-use-waste management sequence. In a life-cycle inventory, this general construct is superseded by a detailed sequence of specific operations that make up each phase (usually illustrated as a block or flow diagram). This sequence forms a product system.

In a typical operation, equipment uses certain inputs to produce outputs. (Energy and materials for maintenance may or may not be included.) The equipment used is itself the result of a series of production steps to build and install it; that is, it is the result of another product system. The energy and material inputs are produced by similar product systems. In turn, other product cycles supply equipment to make the equipment for the earlier product system or the equipment to produce the energy and materials that are supplied to the first product system.

The successive product systems may be termed levels or tiers or, in the mathematical sense, second and higher order product subsystems. A first level (or Level 1), first tier (or Tier 1), or first
order analysis is thus restricted to the inputs and outputs associated with the first level or first tier product system. In a second level, second tier, or second order analysis, the scope of the analysis is extended to include the product subsystems that serve the primary product system. Note that, for example, the total quantity of all releases of a given pollutant in a given subsystem must be added to the quantity of that pollutant released by the distribution or transportation operation in the primary product system being served by that subsystem.

The methodological question here is where to draw the boundary along the links between the primary product system and the subsystems serving it. This is similar to choosing which higher order terms to drop in a mathematical series. In the latter situation, assuming each successive term is smaller than the preceding term, the choice depends on the desired accuracy. Likewise, the corresponding choice in a life-cycle inventory depends on the relative sizes of the contributions from each successive subsystem (ignoring cost, time, and data availability).

Two rules of thumb provide reasonable, analytical means to define boundaries. The first involves interactive analysis and applies to level boundaries. If analysis of a system indicates a change of less than some predetermined fraction of the input-output measures (5 percent, for example), then it is reasonable not to pursue analysis to higher level systems. In this way, a finite analysis may quickly approach asymptotic values. The second approach to setting limits, suitable for comparing two processes, is to define boundaries in such a way as to make their environments essentially the same. This approach applies to both lateral and level boundaries. For example, if two packaging strategies have about the same weight and volume and are both shipped by truck, it may be reasonable to exclude an analysis of shipping from the life-cycle inventory. However, comparisons based on such an analysis would be valid only in terms of differences; ratios might be seriously misleading if absolute inputs and outputs to shipping are large compared with the more restricted system. Recycling is another example. The life-cycle inventory analyst may choose to increase the lateral extent of the analysis to include another product system because the exchange of recycled material is significant.

A third possible rule of thumb does not have a detailed analytical foundation, but it has the advantage of consistency from one application to another, and could form the basis for standardized distribution and transportation models. For example, the transportation boundary is defined arbitrarily to begin at the exit door of a processing or production facility and end at the entrance door of the intended destination. For distribution (warehousing, wholesaling, and retailing), the boundary is defined arbitrarily to start at the end of the trip from the final production facility, and end at the exit door of the distribution facility. This approach works well for life-cycle boundaries.

5.2.3 Inputs and Outputs

Once boundaries are defined for each distribution and transportation activity, inputs and outputs must be described. Clearly, it is impossible to describe every input and output into the system, and aggregation or outright omission is inevitable. Figures 5-3 through 5-6 illustrate some typical distribution and transportation processes. The aim of these classifications is to provide a checklist for the life-cycle inventory to prevent overlooking possible environmental outputs for the specific subdivisions under consideration. Principles of energy and mass conservation within systems are an excellent means of validating inputs and outputs. However, complete adherence to
FIGURE 5-3. A TYPICAL DISTRIBUTION AND TRANSPORTATION PROCESS FOR REFRIGERATED TRUCKS

FIGURE 5-4. A TYPICAL DISTRIBUTION AND TRANSPORTATION PROCESS FOR PIPELINES

FIGURE 5-5. A TYPICAL DISTRIBUTION AND TRANSPORTATION PROCESS FOR ELECTRIC POWER TRANSMISSION LINES
these principles can lead to awkward accounting procedures when ecological or aesthetic outputs are included in a system.

Inputs and outputs for some distribution and transportation systems may also be categorized by carrier, container, and transported product. Each of these subdivisions has its own inputs and outputs. These are indicated in Table 5-2, which provides the classification of outputs. The aim of these classifications is a checklist for the life-cycle inventory to prevent the overlooking of possible environmental outputs for the specific subdivisions under consideration.

**TABLE 5-2. CLASSIFICATION OF ENVIRONMENTAL OUTPUTS**

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A. Carrier</strong></td>
<td></td>
</tr>
<tr>
<td>Operation, Repair and maintenance, Accidental loss</td>
<td>Energy and materials, Auxiliary substitutes, Tools</td>
</tr>
<tr>
<td><strong>B. Containment</strong></td>
<td></td>
</tr>
<tr>
<td>Operation, Repair and maintenance, Accidental loss</td>
<td>Energy and materials, Auxiliary substitutes, Tools</td>
</tr>
<tr>
<td><strong>C. Transported Product</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lost product, Off-spec product</td>
</tr>
</tbody>
</table>
5.3 DATA STATUS

5.3.1 Requirements

Data requirements for the distribution and transportation stages are driven by the specific inputs and outputs associated with each transportation and distribution operation that is defined in a life-cycle inventory. That is, data requirements vary from one life-cycle inventory to another, depending on what distribution and transportation functions are included.

Ultimately, a life-cycle inventory describes the total amounts of various inputs and outputs for each distribution and transportation operation. Those quantities are calculated from knowledge of the amount of the product of interest that is delivered to the end user and of factors relating the amounts of inputs required and outputs produced per unit level of each distribution and transportation operation. For example, the energy required per kilogram of material transported over one kilometer is expressed as MJ/kg-km.

In general, the categories of data required are:

• Energy consumption and form (e.g., MJ/kg-km of diesel fuel)
• Supplies required (e.g., kg wood pallets/kg product moved)
• Energy conversion pollutant emission factors (e.g., air pollutant emission factors in kg NOx/kg-km for diesel engines)
• Product and materials loss rate (e.g., fugitive emissions in kg product loss/kg product moved)
• Discarded and added packing materials (e.g., weight and volume per kg of transported product)
• Accidents (e.g., frequency in number per km, quantity released as average spill size, typical release locations such as highway, roadside, waterway).

A required characteristic of the data is that the assumptions behind each factor be consistent with those of other transportation factors. In addition, where it is logically required, the bases of the transportation factors should be consistent with others on which other components and the overall life-cycle inventory are based.

5.3.2 Sources

Factors exist for some of the preceding data requirements. In life-cycle inventories that have included distribution and transportation, such factors may have been calculated. Unfortunately, they may not be in the public domain. For some data categories, particularly energy use and associated pollutant emission factors, many factors are in the public domain as a result of substantial public interest in energy use, efficiency of energy use, and the environmental impact of energy use.
Proprietary data also exist. Nevertheless, because the comprehensiveness of the available energy and environmental factors is unknown, some may need to be developed.

For those, and for other data categories for which the existence of factors is unknown, many data series exist from which factors can be developed. For example, the U.S. Department of Transportation and the Department of Energy collect and publish many data series on transportation activity and energy use, respectively. The Interstate Commerce Commission has data on accidents. However, it is not known whether the series necessary to construct specific factors exist. In general, though, certain data are likely to exist in connection with economic or environmental regulation or with trade association purposes. An important consideration, and possible limitation, is the uneven quality of the data contained in various series or in derived factors.

5.3.3 Needs

Data do not exist to describe all the inputs and outputs of each distribution and transportation operation. Therefore, work is required to complete the existing set of factors. Generally, more effort is required in the following categories of required data: supplies, product loss, discarded packaging, and accidents.

5.4 GENERIC APPROACHES AND MODELS

5.4.1 Applicability

Distribution and transportation are characterized by relatively few and, for the most part, relatively simple modes with very wide applicability across broad ranges of products and processes. Thus significant opportunities exist to develop generic models and approaches that can have broad utility in life-cycle inventories. Such generic models may include the following modes: trucks, liquid and bulk carriers, trains, pipelines, power lines, and public warehousing.

For example, to create a model of a truck moving between two points, it is essential to assess the various factors affecting that truck, including but not limited to the energy that drives it, the material it is carrying, the emissions released, and the heat and noise generated—all inputs and outputs should be assessed. In fact, a miniature life-cycle inventory for the movement of that truck is required. The above models may be subdivided further into still more specialized generic models such as refrigerated and other environmentally controlled trucks.

Information to develop the above models may be widely available from such sources as industry, the U.S. Department of Transportation, trade associations, and engineering schools. Highly specialized distribution and transportation technologies can reasonably be characterized by analogy with more conventional forms.

Generic modeling will create a database that can reduce duplication, decrease costs, and lead to standardized methods. Specific modifications and amendments to the generic model may then be carried out to make it address issues related to the transportation of a particular product. As an example, data related to the transport of liquid beverages will require the application of a volume/weight factor that is different from that for the transport of facial tissue.
5.4.2 Limitations

Generic distribution and transportation models are not without limitations. The boundaries of generic distribution and transportation operations will have to be chosen carefully to match those of readily available distribution and transportation data (see Section 5.3.2). Boundary assumptions of available trade or government data are probably not uniform (or even explicit), but it may be possible to apply appropriate correction factors to achieve something approaching uniform standards. Similarly, in choosing boundaries for a particular life-cycle inventory, care should be taken to match the boundaries used in any generic models that are applied.

Generic distribution and transportation models may not work well in highly interactive, heterogeneous power networks. As a simple example, cogeneration of steam and electricity from a single fuel source should not be viewed as the additive combination of generic steam and electricity distribution models.

Routing schemes can have a large impact on the efficiency of some transportation industries. When a single vehicle is used to deliver a variety of materials to different locations, the choice of a route may have a significant impact that would not be captured in generic distribution and transportation models.

5.5 RECOMMENDATIONS FOR FUTURE DEVELOPMENT OF THE DISTRIBUTION AND TRANSPORTATION STAGE

5.5.1 Data

Life-cycle inventory databases, or more generally data sets, may contain available information on transportation vehicle emissions and energy utilization and maintenance (wear and tear) information. Research and development, figures, measurements, and specifications created as a result of the development of the input and output factors used in transportation and distribution models may be beneficial. Information on accidents and other mishaps that relate to the transportation and distribution of hazardous and toxic materials is also important. It is advisable to include all other data required for the development of life-cycle inventories. Information collected from distribution and transportation databases in the public domain must specify source and periodically be updated and maintained. Work is needed to suggest ways to standardize organization, documentation, units, and other parameters.

Database information should not be limited to those transportation modes and their outputs that are related to the environment. Rather, information related to already completed life-cycle inventories carried out in the areas of distribution and transportation should also be compiled. This will assist investigators in their studies and reduce the time and cost of their life-cycle inventories.

Information collected should also cover areas for the supporting systems associated with distribution and transportation, including the outputs related to roads, bridges, railway tracks, pipeline, and power lines. It is important to differentiate between the outputs created by the construction of such supported systems and those associated with their use, and to keep the data describing them distinct.
Data are the foundation of life-cycle inventories and should be widely available, accurate, and current. Public data sets—collections of data assembled or developed and maintained in the public domain—have been suggested to address those objectives. However, in reality, proprietary and practical considerations may limit the ability to develop public data sets.

Considering public data sets raises questions that may shed light on the practical issues of developing them:

- Building a database versus using disparate but consistent data sets, some of which may be databases
- Means to assure accuracy, representativeness, and currentness
- Developing generic models
- Institutional sponsor(s)
- Cost of building and maintaining the collection.

A specific idea for investigation, whether or not a formal public data set is established, is the interest and feasibility of industrial and similar associations to enhance the accuracy, representativeness, and currentness of the collected data. Such associations may be willing, without providing specific data, to confirm that certain data about which their members are knowledgeable are reasonably realistic.

5.5.2 Standards

The disparity of approaches in selecting criteria in life-cycle inventories is recognized. An investigation of the feasibility of developing principles and conventions for life-cycle inventories should be investigated; these principles and conventions might, for example, be useful in the input and output itemization. Another example would be conventions for data reporting.

An examination of the principles behind generally accepted methodologies, such as accounting procedures and ASTM standards, may help to extract useful ideas and suggestions for the development of a similar framework for life-cycle inventories. Such standard principles can be useful in formulating life-cycle inventories as well as in reviewing them, and perhaps eventually in certifying their adherence to these accepted principles. Areas in distribution and transportation where development of principles and conventions is likely to provide benefits include nomenclature, units, data tables and databases, and allocation of inputs and outputs.

5.5.3 Generic Models

Although generic distribution and transportation models should be used with caution, they have potentially high utility in a wide variety of industrial life-cycle inventory applications with relatively simple distribution networks. (One reason for keeping life-cycle inventories as simple as possible is to facilitate the appropriate use of generic distribution and transportation models.) Generic distribution and transportation models can reduce duplication of effort, reduce life-cycle inventory costs, and encourage the development of life-cycle inventory standards.
Early life-cycle inventory projects that examine truck and rail transportation, electrical power distribution, pipelines, and warehouse and retail outlets could substantially facilitate later life-cycle inventories that examine broader industrial issues. For this reason, the development of generic distribution and transportation life-cycle inventory models deserves consideration as a priority item in the national life-cycle inventory effort.

5.5.4 Selection of Appropriate Boundary Conditions

With respect to life-cycle boundaries, research is needed in collaboration with people knowledgeable about operations within the various components to identify such distribution and transportation operations. The objectives would include characterizing them to the degree necessary to decide whether each should be treated separately as a distribution and transportation operation or taken as a unit with respect to the component operations. In either case, the contributions of the distribution and transportation operation to energy and materials requirements and to waste should be included. In the second approach, the distribution and transportation operation would be characterized as described in this chapter. An alternate approach might be to treat it as an input and output set. Research would establish information useful for selecting the boundary conditions appropriate for any given life-cycle inventory.

Research in the area of lateral boundaries should focus on searching for and describing any linkages among distribution and transportation systems, such as highly integrated or comingle production steps and including transfers of recycled materials between production steps. Information developed would help analysts determine the appropriate life-cycle inventory scope for any given case.

Research is needed to offer guidance on how to set the level boundary conditions. Case studies could show the relative magnitudes of contributions from various levels. Then, for the same or similar cases, the life-cycle inventory analyst could anticipate the approximate inaccuracies introduced by ignoring various higher levels and consider that information in conjunction with other inaccuracies or uncertainties in planning the life-cycle inventory. It may be possible to formulate a rule of thumb that each level’s contribution approximates a certain percentage of the next higher level.

One research objective is to understand the implications of employing different levels for different distribution and transportation operations in the primary product systems. Recognizing that the data requirements probably grow exponentially as higher order subsystems are incorporated, it is desirable to work as close to the primary level for as many primary product system operations as possible. The research may reveal that, for certain distribution and transportation operations, lower order subsystems contribute a large fraction of the total release, but that the opposite is true for middle and higher order subsystems. The latter might then be validly ignored in most cases, or be approximated by an adjustment factor, whereas the former may not. A similar comparison between primary operations may also permit reasonable approximations.
CHAPTER 6.0

USE/RE-USE/MAINTENANCE

The treatment of the use/re-use/maintenance (U/R/M) stage of a life-cycle inventory has important ramifications, whether the information is used for internal decisions, public information, or public policy decisions. This section deals with specific issues that need to be addressed to quantify this stage of a life-cycle inventory. Topics to be presented, discussed, and in some cases resolved are:

1. Boundaries and scope of activities
2. Activities in the U/R/M stage
3. Data sources, methodologies, and deficiencies
4. Incorporation of end-use patterns
5. Presentation of inputs, outputs, and reporting format
6. Overall recommendations and research and development needs for future life-cycle inventory development.

Limitations and problems with life-cycle inventories, along with specific definitions of important terminology, will be addressed in the sections to follow.

6.1 BOUNDARIES AND SCOPE OF ACTIVITIES

The use/re-use/maintenance stage of a life-cycle inventory consists of a discrete set of activities that begins after distribution of finished products or materials to an end user takes place and ends at the point at which those products or materials are discarded and enter a waste management system. The boundaries and scope of activities of the U/R/M phase are briefly delineated below and illustrated in Figure 6-1.

U/R/M begins when a finished product arrives in the hands of an end user at the point of use. End users are defined as entities (individual consumers, commercial businesses, institutions) that actually use (unpackage and consume, operate, store for later use, or prepare for use) a finished product (a product in the form in which it will be used, including any primary packaging). Thus, an end user could be an individual who consumes a beverage or a hospital that provides a beverage to a patient.
The actual delivery of a finished product to an end user is considered part of the distribution stage, and therefore outside the U/R/M boundary. This is the case whether the product arrives by mail or other direct delivery, by purchase from a service outlet (e.g., take-out restaurant), or by transport from a retail store to the site of use by the end user (groceries brought home).

Packaging associated with a product is allocated along the same lines: packaging associated with delivering products to a retail store (shipping boxes) or displaying products at the store is allocated to the distribution phase, whereas packaging that accompanies a product to the point of use and is removed by the end user is allocated to the U/R/M stage.

U/R/M ends when a material or product has been used by an end user and is discarded. Beyond this point, the material or product enters either the recycling or the waste management phase. For example, laundry detergent exits the U/R/M stage when it is discharged down the drain; leftover food exits when it is placed at the curbside or delivered by the end user to a landfill or transfer station as a waste.

### 6.2 ACTIVITIES IN THE USE/RE-USE/MAINTENANCE PHASE

Figure 6-2 is a flow diagram of the activities in subcategories within the U/R/M phase, which are briefly described below.

**Use.** Use includes activities such as consumption of a product, operation of equipment, storage of a product for later use (e.g., refrigeration), preparation of a product for use (e.g., cooking), and so forth.

**Maintenance.** Maintenance may occur at the site of the end user or at another site. It includes activities such as on-site (e.g., home) repair, off-site repair by a repair service, and preventive maintenance (e.g., changing oil in a car). On-site maintenance may require trips away from the site to obtain supplies and then back to complete the maintenance activity. Off-site maintenance includes transport to and from the site of the maintenance facility.

**Re-Use.** Re-use includes on-site (e.g., home) re-use and off-site re-use. On-site re-use may include intentional re-use of a product or package for its original purpose or incidental re-use for a different
FIGURE 6-2. ACTIVITIES INCLUDED IN THE USE/RE-USE/MAINTENANCE STAGE
purpose (e.g., storage of paint brushes in an old mayonnaise jar). Off-site re-use includes donations of used items to charities for re-use by another party and rental of equipment or another item from a rental service. Off-site re-use also includes the return of materials to a retailer or manufacturer to be re-used for their original purpose (e.g., a refillable beverage bottle). In this last case, the returned materials leave the U/R/M phase at the point of collection and then re-enter the manufacturing phase.

6.3 DATA SOURCES, METHODOLOGIES, AND DEFICIENCIES

Data are required to measure and model the parameters of product U/R/M, both to determine the resource and pollutant release inputs and outputs associated with consumption of the product or service and to translate the physical production units of a product or service into product functionality. This is especially necessary when comparing alternative products or services that provide the same function. Three basic approaches that have been used to determine the parameters of, and data for, the analysis of product U/R/M are:

- Primary data collection, whereby the consumer or a party directly associated with this stage of the product life cycle describes how they use the product
- Secondary data, whereby published data, studies, articles or surveys are used
- Assumptions, whereby the investigator makes assumptions about the parameters of product use.

The approaches can also be characterized as macro or top-down, which tend to be based on secondary data, or a mix of secondary data and limited primary data; and micro or bottom-up, which tend to be based principally on primary data. No single data collection method or source is usually sufficient for a life-cycle inventory. Furthermore, each has advantages, disadvantages, and limitations, as described below.

6.3.1 Primary Data Collection—Statistical Sampling

6.3.1.1 What Information Can Statistical Sampling Provide?

Primary data collection designed to capture information on a representative sample of end users can provide current information on the parameters of product or service use; for example:

- How long a product or service is used before discard (e.g., the number of years a television set has been in use and is expected to be in use)
- Other material used in conjunction with product use or maintenance (e.g., laundry soap or bleach to wash a reusable cloth product)
- Frequency of product repair or maintenance (e.g., how often an appliance is repaired over its lifetime, and who does the repair)
- Other uses of the product beyond its original purpose
- What the end user does with the product when they are through with it.
Frequently, the end user will not be able directly to supply information on inputs and outputs. However, the end user can provide data on user practices from which inputs and outputs can be derived. Generally, the end user can be the source information from which the energy, materials, and pollutant release inventory can be derived. However, the end user usually will not be aware of that information. (An exception would be an institutional or commercial end user who may have some information on energy consumption or water effluents.)

This category of primary data collection can take several forms:

- A telephone survey, whereby members of the studied population are selected from a list according to a sequence specified in an experimental design

- A mail survey, whereby members of the studied population are selected from a list and mailed the survey instrument

- Panels of end users that maintain diaries about product use

- Personal interviews, whereby members of the studied population are preselected and visited personally to collect data

- Mall (or other location) intercepts, whereby members of the studied population are approached and interviewed.

Each form has associated advantages and disadvantages, discussed below in Section 6.4.1.4. Life-cycle inventories done recently generally do not include primary data collection of this quality. However, a set of REPA studies on three consumer products (diapers, napkins, and towels) were based on a statistically valid national household survey to determine consumer U/R/M (Barber et al., 1977a,b). The methodologies associated with primary data collection of this type are well known and codified. Furthermore, the methods are widely used in market research by both consumer and industrial products manufacturers. In virtually all cases, the research is done by an independent survey research company.

6.3.1.2 Phases

Primary data collection intended to be statistically representative has common phases:

- **Experimental Design and Protocol**—A description of the objectives of the research, population of interest, sufficient information to determine the required sample size (including the expected nonresponse rate), the source of the list to be used for the sample selection, the sampling frequency, procedure for handling nonrespondents (telephone, in person, and intercepts), the survey timeframe and any other information necessary to describe the way the data will be collected.

- **Survey Instrument**—The questionnaire used to collect the data, which usually includes the instructions provided to the interviewer. The survey instrument includes demographic or other questions to characterize the respondents.
• **Data Tabulation and Extrapolation**—Including sufficient straightforward (simple) tabulations of the data to demonstrate that the sample is representative, as well as a description of the method used to extrapolate the sample to the studied population.

### 6.3.1.3 Results Reported

Studies reporting complete survey results should describe the methodology phases described above, including the sampling procedure, experimental design, and a copy of the survey instrument. In addition, a data appendix should contain simple data tabulations.

### 6.3.1.4 Issues

The major issues associated with statistical sampling, even if well designed, as a data collection for a life-cycle inventory or for any other application, include the following:

- **Cost**—If studying a widely used product with relatively simple U/R/M parameters, it may be included in a larger national survey that would cost from $15,000 to $30,000 (1990 $US). However, if the product (or one of the products) being studied is used by a small segment of the population or the U/R/M pattern is more complex, a custom primary data collection effort would be required, and the associated cost would be on the order of $30,000 to many times that amount.

- **Representativeness of the Sample**—Do the demographic and other characteristics of the sample correspond sufficiently closely to the studied population to represent the population? This can be determined by a statistical analysis of the results.

- **Bias in Questionnaire Design or Administration**—The phrasing of the questions and the sequence in which they are asked affects the response.

- **Respondent Bias**—This includes the Hawthorne effect (i.e., the act of questioning or observing through a panel changes behavior) and respondents providing answers they think the interviewer wants to hear or they believe are the “correct” answers.

- **Statistical Interpretation**—How the investigator used the data and utilized it in the life-cycle inventory.

- **Nonrespondent Bias**—Whether the nonrespondents (e.g., those not at home for a telephone survey, those that don’t respond to a mail survey, and those that refuse to participate) are likely to be different in terms of product U/R/M than the respondents.

### 6.3.2 Other (Limited) Primary Data Collection

Other primary data collection includes surveying parties that are associated with this stage of the product life cycle. This type of data has been used more recently in life-cycle inventories. The data collected may or may not be a representative sample, but generally represent a small sample of the population of interest. Examples include:

- Focus groups (eight to fifteen people) of end users
• Manufacturers of equipment associated with product use, such as washing machine manufacturers

• Suppliers of raw material or a service associated with product use, such as a commercial laundry facility

• Trade associations and professional societies that may compile secondary data (see Section 6.3.3.) or may be able to direct the investigator to parties who may have the information

• Universities and other institutions engaged in research related to the product.

6.3.2.1 What Information Can Limited Primary Data Provide?

Investigators are seeking the same type of information using limited primary data collection as with the representative sampling approach. However, the number of people included and/or the method per se are not amenable to statistical extrapolation to the population of interest.

On the other hand, suppliers or manufacturers whose products are associated with the consumption process can often provide product design information (e.g., capacity of a washing machine, electric energy consumption associated with its use with the product of interest, etc.) that the end user does not know. Universities and other research institutions may have research information that has not yet been published or may be able to direct the investigator to published information he/she would not otherwise find.

6.3.2.2 Phases

Focus groups and other small sample methods have similar phases as primary data collection based on statistical sampling. However, the entire process is simpler.

• Experimental Design—When using focus groups, generally they are selected based on demographic criteria or other characteristics of the population of interest. Group size, geographic location, and other composition characteristics would be specified. For surveys of manufacturers or services used in conjunction with the product of interest, the experimental design may be simply “contact the three largest manufacturers of washing machines.” Where an industry does not have a great deal of diversity in these products or services, this may be sufficient information from which to derive some of the necessary resource and pollutant release information.

• Survey Instrument—When using focus groups, a moderator’s guide will be prepared to enable the moderator to be sure the topics of interest are covered. However, the purpose of focus groups as a data collection device is to provide for the free exchange of issues and information about the topic of interest. For surveys of manufacturers or service providers, an interview guide or questionnaire is usually prepared, but it may be no more than a list of the three or four specific things to ask the company’s representative.
• **Data Tabulation**—Focus group results do not lend themselves to simple data aggregation. Upon review of the audio tapes, the investigator may be able to quantify some items. However, the sample across focus groups may be too small to enable any type of quantitative conclusion.

### 6.3.2.3 Results Reported

Focus group data should be summarized in the manner indicated above for data tabulation. When using other small sample data sets, the investigator should indicate the number of respondents and summarize the data. In this case, as in most primary data collection, the identity of individual responses (i.e., matching a specific number with a respondent) may not be possible; most of the time, respondents will only cooperate if their specific data are aggregated or coded in some fashion. For other primary data contacts, the tabulation should include a list of the contact (name, address) and identification of the information provided.

### 6.3.2.4 Issues

The issues associated with small sample or limited primary data collection are similar to those encountered with statistical sampling. However, in the case of statistical sampling, some of the issues can be resolved by review of the experimental design and the way results are reported. In this case, there is greater uncertainty about the representativeness of the data and bias either in the way questions were asked or in the way those interviewed responded. Therefore, sensitivity analyses should conform to the level of certainty of the data.

The major advantages of small sample or limited data collection are time and cost. Focus groups, the most expensive of these methods, can cost as little as $7,500 to $15,000 apiece, depending on the criteria for group selection, whether the focus group participants need to be paid, and the geographic location. The cost of collecting other limited primary data is a function of the time required for each contact and the number of persons contacted.

### 6.3.3 Secondary Data Sources

Secondary data sources are any published or unpublished data, articles, studies, or reports reflecting the results of previous data collection and analysis that are available in published form. In many cases, a good, recent study may be a better, more comprehensive data source than limited primary data collection. Most secondary research was done for a purpose other than to determine the resource and pollutant effluent levels or product U/R/M characteristics.

Examples of secondary data sources include the following:

- Trade or industry statistical reports indicating unit sales and other product data, as well as other data from trade associations, industry or professional associations

- Federal government statistical data on product sales, consumption of materials, and so forth (e.g., Census of Manufacture and related documents)

- Industry market research studies done to describe consumer purchase behavior
• Federal agency studies of specific products (e.g., the Consumer Product Safety Commission, Food and Drug Administration, Environmental Protection Agency)

• For products that have been the subject of state or federal rule making or policy setting actions, the docket or hearing record associated with those proceedings, including filings by manufacturers and other interested parties

• Articles in the trade press or professional journals.

The ways to find secondary data include the following:

• Computerized database literature searches depend on key words as the basis for locating information, and the ability to identify sources are a function of the breadth of the databases accessed as well as the ability to match on the key words.

• Predicasts, a subscription service that may be available in business libraries, summarizes a variety of published statistics, indicating the source of each. It is useful to identify trade press articles that may have information of interest.

• The U.S. Environmental Protection Agency’s Pollution Prevention Clearing House.

• References used in other published studies.

• Contacting individuals in trade associations, government agencies, universities, and professional organizations to identify sources as well as data.

6.3.3.1 What Information Can Secondary Data Provide?

Because secondary data represent information created for another purpose, it may or may not directly provide U/R/M information. However, it may provide a basis for estimating or provide directly such data as:

• Useful life of a product (e.g., trade press articles on the average length of time people keep new cars)

• Maintenance or repair data (e.g., Consumer Reports assessments of appliances)

• Methodologies used in the past to estimate U/R/M parameters of interest that can be applied to current data to obtain current estimates.

6.3.3.2 Reporting

When secondary data sources are used, it is important to indicate the breadth of the search undertaken. When a secondary source is used directly for a particular data phase, it should be referenced as such. When a secondary source is used either as a methodology or as a basis of deriving a parameter or estimating a data phase, it should be referenced, and the fact that derivation or estimation was involved should also be indicated.
6.3.3.3 Issues

The principal issue associated with secondary data sources is that they were designed for another purpose. Thus, care must be taken in their use. In addition, they should be reviewed for the various biases described for primary data. The issues can be summarized as follows:

- **Timeliness**—By definition, secondary data sources were created at some time prior to the current study. It is important to ensure that the information is representative of current practice (if that is how the secondary data are being used).

- **Bias**—If the secondary data are based on primary data, they would need to be checked for all the biases that may be found in primary data (see discussion above).

- **Cost**—Use of secondary data is generally less costly than collecting primary data, but can require as much time.

- **Uncertainty**—The completeness or variability of data reported in secondary sources can render uncertain the accuracy of a particular parameter or data item. In this case sensitivity analysis on the data and parameter bases of the variability observed can address this concern.

6.3.4 Assumptions

Assumptions are necessary when primary or secondary data sources or methods of estimation are not available. Assumptions can be based on data that are not specific to the product or service being analyzed. For example, information may be available about washing a load of laundry, but not specifically about a particular article of clothing. The assumption in this situation is that a general, known data phase (washing a load of mixed laundry) can be applied to (washing) the specific product.

In other cases, a U/R/M parameter or data may be assumed because either general or specific data are lacking.

6.3.4.1 What Information Can Assumptions Provide?

Assumptions provide a way of generating parameters or data necessary to the analysis. In most cases, data and parameters are not fully available. Thus some assumptions are necessary in virtually all life-cycle inventories. The extent and importance of assumptions will vary from case to case.

6.3.4.2 Reporting

Critical to reporting assumptions is to state clearly what the assumptions are and to distinguish data or parameters based on assumptions from those based on other sources. In addition, the sensitivity analysis of the assumptions provides a basis for determining how important the assumptions are to the analysis.
6.3.4.3 Issues

The key issue associated with the use of assumptions is their effect on the results of the analysis. This issue can be addressed through sensitivity analysis to varying degrees, depending on the specific case. For example, if the investigator does not know anything about the distribution of the values of a data item, the sensitivity analysis will be based on additional assumptions about the data item. However, the sensitivity analysis will still be useful to indicate the relative importance of the assumption in the analysis.

6.3.5 Integration of Data Sources to Model and Describe U/R/M

Table 6-1 summarizes the types of data sources that may be appropriate for various components of the U/R/M. In each component, the end user directly involved can provide information on U/R/M patterns. The end user (especially a consumer household) will not have information on inputs and outputs, except for raw materials.

6.4 INCORPORATION OF END-USE PATTERNS

Though the useful life of a product may not always be explicitly defined in a life-cycle inventory, it must nonetheless be included in analyses related to product U/R/M. For example, to determine how many cloth diapers must be manufactured to support an infant over a given period of time, one must know how frequently the infant is changed (and therefore the number of diapers)

| TABLE 6-1. COMMON DATA SOURCES FOR COMPONENTS OF USE/RE-USE/MAINTENANCE |
|---------------------------|---------------------------|
| Maintenance and Use       |                          |
| Use parameters            | End users, Manufacturers of related products and services | Previous studies, Published statistics, etc. |
| Re-Use                   |                          |
| End user                 | End user                 |
| Manufacture              | Manufacturer              |
| Rental                   | End user, Rental shop    |
| Donation                 | End user, Donee           |
| Repair                   | End user, Repair shop    |
| Inputs and outputs       | Manufacturer of related products and services | Energy (see Chapter 3) |
| Transport                |                          |
| Patterns                 | End user, Municipalities | Previous studies |
| Inputs and outputs       | Vehicle                  | (see Chapter 5)  |
and the number of washings the diaper will withstand before it must be discarded. In a similar way, one must know how many times a refillable soft drink container will actually be returned by consumers (before disposal or breakage) to determine how many such containers must be manufactured to deliver a given volume of beverage. In these examples the useful life cannot be simply a stated period of time the product, package, or service will last, but must be defined in terms of actual end-use patterns.

In the same way one must be careful to consider use patterns of improved performance products or services. Unless end users modify their behavior, the new product may actually have negative impacts over its life cycle. Two examples illustrate this point. First, a consumer may need fewer high-absorbency paper towels to mop up a spill than normal towels. If the consumer of this improved product, however, rolls off the same number of high-absorbency as normal sheets, then discards them after one use, no savings are realized. The same situation can exist for detergents. If a detergent’s composition is modified to reduce water emissions, but consumers use more laundry additives to compensate for a perceived loss of cleaning power, the impact of this new product plus the increased additives may be greater than that of the current formulation. It is, therefore, imperative that actual end-use consumption patterns be considered when performing a life-cycle inventory.

Such use information is available, but typically not through public sources. Most companies thoroughly study their product’s or service’s use as a means of improving sales. End-use data is derived from analyses of such information as sales, inventories, and purchases. For consumer products companies, marketing studies are also conducted with actual consumers, such as focus groups, mall intercept interviews, and diary panels. One drawback for such data, however, is that many times it is considered proprietary or confidential by manufacturers.

For these reasons, wherever possible data on actual use patterns should be the basis for any use characterization in a life-cycle inventory. Where such data are not available (i.e., New Product Development/Manufacturer’s Confidentiality), it is important that all assumptions used as the basis for use characterization be clearly stated.

6.5 PRESENTATION OF INPUTS, OUTPUTS, AND REPORTING FORMAT

The previous life-cycle steps (raw materials, manufacturing, and distribution) most likely incorporate data in their analyses by using the normal units of production (kilograms of raw material, grams of an ingredient, units of production). The U/R/M step of the life cycle contains information about the useful life of the product or service and how it is used. This should be the basis of presenting the results in the agreed upon format.

The data from all previous process steps must be translated into functional use equivalents. Some examples of what this means follow:

- A study of beverage containers should compare all inputs and outputs for alternatives based on a fixed quantity of product (e.g., 1,000 liters of beverage) or a specific number of standard servings (e.g., 250-ml servings, the serving size on a nutrition label).
• Where the products being compared have different use frequencies to achieve the same functional result, all inputs and outputs should be based on an equivalent functionality.

• Where the products being compared have similar use frequencies (but may have different useful lives or frequencies of maintenance or repair), all inputs and outputs should be reported in equivalent uses (not units).

This is accomplished by applying a conversion factor to data generated from other steps in the life cycle. The conversion factor will be based on the useful life of the product and patterns of use.

6.6 RECOMMENDATIONS AND RESEARCH AND DEVELOPMENT NEEDS FOR FUTURE LIFE-CYCLE INVENTORY DEVELOPMENT

6.6.1 Recommendations for Data Reporting

Primary Statistical Data. Studies reporting complete survey results should describe the methodology phases described above, including the sampling procedure, experimental design, and a copy of the survey instrument. In addition, a data appendix should contain data tabulations.

Limited Primary Data.

• Focus group data should be summarized in the manner indicated for data tabulation.

• When using other small sample data sets, the investigator should indicate the number of respondents and summarize the data. In this case, as in most primary data collection, the identity of individual responses (i.e., matching a specific number with a respondent) may not be possible; most of the time, respondents will only cooperate if their specific data are aggregated or coded in some fashion.

• For other primary data contacts, the tabulation should include a list of the contact (name, address) and identification of the information provided.

Secondary Data. When secondary data sources are used, it is important to indicate the breadth of the search undertaken. When a secondary source is used directly for a particular data phase, it should be referenced as such. When a secondary source is used either as a methodology or as a basis of deriving a parameter or estimating a data phase, it should be referenced, but the fact that derivation or estimation was involved should also be indicated.

Assumptions. Critical to reporting assumptions is to state clearly what the assumptions are and to distinguish data or parameters based on assumptions from those based on other sources. In addition, the sensitivity analysis of the assumptions provides a basis of determining how important the assumptions are to the analysis.

6.6.2 Recommendations for Dealing with Data Issues

The issues associated with primary data collection are similar whether dealing with small sample or limited primary data collection are similar. However, in the case of statistical sampling, some of the issues can be resolved by review of the experimental design and the way results are
reported. In this case, there is greater uncertainty about the representativeness of the data and bias either in the way questions were asked or in the way those interviewed responded. Thus, sensitivity analysis should be done consistent with the level of certainty surrounding the data.

The completeness of the data or variability in data reported in secondary sources can be sources of uncertainty about the accuracy of a particular parameter or data item. In this case sensitivity analysis on the data/parameter bases on the variability observed should be used to address this concern.

The key issue associated with the use of assumptions is their effect on the results of the analysis. This issue can be addressed through sensitivity analysis to varying degrees, depending on the specific case. For example, if the investigator does not know anything about the distribution of the values of a data item, the sensitivity analysis will be based on additional assumptions about the data item. However, the sensitivity analysis will still be useful to indicate the relative importance of the assumption in the analysis.
CHAPTER 7.0

RECYCLING

This chapter discusses specific issues associated with development of the recycling stage of a life-cycle inventory. Composting is included as a specialized form of recycling.

Described below are the boundaries and activities included within the recycling stage and its interfaces with the U/R/M, waste management, and manufacturing and processing stages. A description of models for closed- and open-loop recycling systems is presented, along with suggested methodologies for allocation of inputs and outputs among products in multiproduct systems. The issue of uncertainty in projection of future recycling rates is highlighted. Finally, data sources and collection methodologies are discussed, along with their deficiencies and areas of needed future research.

7.1 BOUNDARIES AND SCOPE OF ACTIVITIES

Recycling (including composting) has alternatively been viewed as an aspect of either the U/R/M phase or the waste management phase. However, recycling is perhaps best viewed (and for the purposes of this report, will be viewed) as a discrete phase that takes materials out of the hands of the user, thereby diverting them from the waste management system, and delivers them to the manufacturing or processing sector. The activities in the recycling stage are discussed below and illustrated in Figure 7-1.

Recycling (including composting) begins when a discarded material or product is delivered to a collection system for the purpose of recycling: when a bottle is placed in a curbside bin in a community that has curbside collection for recycling or is taken to a drop-off recycling center, or when leaves are raked up and bagged for pickup by a composting operation.

Recycling thus includes the collection and handling of the materials, plus any processing (washing, crushing, baling) that is needed to prepare and deliver the material to re-enter a manufacturing system as a raw material. For glass, preparing cullet to enter a glass furnace would be included, including delivering the cullet to the furnace facility. For newspaper, de-inking the paper (to render it effectively equivalent to a virgin pulp source) would be included, as would transporting the newsprint to the de-inking plant.

7.2 ACTIVITIES IN THE RECYCLING STAGE

7.2.1 Background

Applying inventory methodologies to the recycling area is confounded by multiple sources and routes of recycled materials. Definitions must first be clarified. Recycled content is of two types,
FIGURE 7-1. ACTIVITIES INCLUDED IN COMPOSTING AND RECYCLING
pre-consumer and post-consumer. Pre-consumer recycled materials are materials and byproducts that have not reached a consumer for an intended end use and have been recovered or diverted from solid waste, but are not those typically re-used within an original manufacturing process. Post-consumer recycled materials are those that have served their intended end use by a business, consumer, or institutional source and have been separated from municipal solid waste for the purpose of recycling.

Recyclability is defined by reference to an actual recycling rate as measured in the area set by the study scope (e.g., state, region, nation). Possible recycling scenarios are open-loop and closed-loop systems. In a closed-loop system, the product is recycled back into a similar product as illustrated in Figure 7-2. In this case, when a product is recycled, it has avoided the impacts associated with disposal and production of the primary material, but generates impacts associated with recycling (e.g., transportation, washing, shredding) and any converting impacts incurred as a result of using recycled materials instead of virgin materials.

![Figure 7-2. A CLOSED-LOOP RECYCLING SYSTEM](image)

The other recycling scenario is open-loop, in which a product is recycled into an alternate product, as illustrated in Figure 7-3. In this case, the system includes two distinct products. The overall change in the system (compared with Products 1 and 2, each being independently produced and disposed of) is that Product 1 has reduced or eliminated disposal, whereas Product 2 has avoided production of virgin material. In addition, inputs and outputs associated with recycling and any converting changes made in Product 2 to use recycled over virgin materials are added to the system.

Often products do not undergo open-loop or closed-loop recycling exclusively; the ratio is dictated by economics, market demand, health issues, etc. Additionally, open-loop recycling often does not involve only one additional product. For instance a plastic soda bottle can be recycled into carpet fiber, insulation, cleaning product bottles, and park benches. Similarly, the recycled content in a product can come from multiple sources. An example is recycled paperboard boxes, which may
use variable ratios of recycled newsprint, old corrugated containers, box cutting trim, office paper, or mixed wastepaper.

The definition of open-loop or closed-loop recycling is not based upon number of times an item is recycled. This is taken into account when looking at actual recycling rates and recycled content levels and is explained further in Section 7.2.2.

Composting can be thought of as a form of open-loop recycling, where Product 2 is compost or topsoil.

### 7.2.2 Methodology

#### 7.2.2.1 Closed-Loop Recycling

The following information is needed to describe fully a pure closed-loop system:

A. All inputs and outputs associated with production of the primary material (from raw material acquisition to the point at which recycled materials would be processed as if they were virgin materials).

B. All inputs and outputs associated with disposal of the product of concern (referred to as Product 1 in Figure 7-2). This includes transportation, solid waste, incineration emissions, and all others identified in the waste disposal section.

C. All inputs and outputs associated with recycling of Product 1. This includes transportation (to drop-off sites, to a materials recovery facility [MRF] to a processor), energy to reprocess back into a raw material (to clean, shred, re-pulp) and wastes associated with this reprocessing (fines, biological oxygen demand, cleaning agents).
D. All inputs and outputs associated with a no recycling system for Product 1 (i.e., only the left side of Figure 7-2).

E. Any inputs and outputs from converting Product 1 with recycled materials instead of virgin materials.

The net inputs and outputs, N_{I/O}, of a closed-loop recycling system, as opposed to a disposal system, are determined by this formulation:

\[ N_{I/O} = D - B(a) - A(b) + C(a) + E \]

where \( a \) = recycling rate and \( b \) = recycled content level. Therefore, items recycled at a high rate subtract more disposal inputs and outputs, and items with high recycled content subtract more primary material production inputs and outputs. It is not likely that \( a \) and \( b \) will be equal in a closed system because of material lost during recycling and other recovery limitations.

This has been simplified for explanatory purposes and is not meant to imply that all wastes and types of energy can be added up and multiplied by factor \( a \) or \( b \). Each individual waste or energy type would have to be adjusted in this manner so that no specificity is lost in presenting final results.

### 7.2.2.2 Open-Loop Recycling

In rare cases, a product may undergo an exclusively closed-loop recycling process. Real-world systems involve many items being recycled into a product, which itself could be recycled into many items. For simplicity, however, consider the case in Figure 7-3. The overall difference between this system and the two independent systems is that Product 1 has avoided disposal and Product 2 has avoided virgin material production. In addition, recycling inputs and outputs have been added to the system, as have any converting inputs and outputs resulting from use of recycled materials instead of virgin materials in Product 2.

To look at the net inputs and outputs of this open-loop recycling system, one should know:

A. All inputs and outputs associated with production of the virgin material for Product 2 (from raw material acquisition to primary material production).

B. All inputs and outputs associated with disposal of Product 1. This includes transportation, solid waste, incineration emissions, and all others identified in the waste disposal section.

C. All inputs and outputs associated with recycling of Product 1. This includes transportation (to drop-off sites, a MRF, processor), energy to reprocess back into a primary material (to clean, shred, re-pulp) and wastes associated with this reprocessing.

D. All inputs and outputs associated with a no recycling system for Product 1 (i.e., only the left side of Figure 7-3).

E. All inputs and outputs associated with a virgin system for Product 2.
F. Any converting inputs and outputs incurred as a result of Product 2 using recycled materials over virgin materials.

The net inputs and outputs, \( N_{I/O} \), of an open-loop recycling system are determined by this formulation:

\[
N_{I/O} = D + E - B(a) - A(b) + C(a) + F
\]

where \( a \) = recycling rate of Product 1 and \( b \) = recycled content level of Product 2.

### 7.2.2.3 Evaluating Recycling Systems

Life-cycle inventory users are not usually interested in a system; they are often interested in a particular product and how that product might relate to others outside the system. In order to evaluate a particular product (i.e., only Product 1 or only Product 2), a method is needed to allocate these overall system impacts among the individual products. There is no scientifically valid way of separating this system into individual product components; any method is purely arbitrary. Two methods commonly used follow.

1. **Equally divide impacts added to the system because of recycling.** The inputs and outputs associated with recycling are: reduced disposal of Product 1, reduced virgin material production for Product 2, inputs and outputs associated with recycling, and any converting net inputs and outputs incurred as a result of using recycled materials over virgin materials in Product 2. If these are divided in half, net inputs and outputs for Product 1 are as follows:

\[
N_{I/O} \text{ (Product 1)} = D - \frac{1}{2} \left[ B(a) + A(b) - C(a) - F \right]
\]

Net inputs and outputs for Product 2 are as follows:

\[
N_{I/O} \text{ (Product 2)} = E - \frac{1}{2} \left[ B(a) + A(b) - C(a) - F \right]
\]

This approach offers several advantages: it eliminates the possibility of double-allocating recycling credits and debits, minimizes arguments over which product should receive credits or debits, and enables independent evaluation of a product.

Limitations are that the 50/50 split is arbitrary and not a measure of which party made the effort to implement the recycling change (e.g., manufacturer, recycler, municipality). Also, the impacts of virgin material on Products 1 and 2 must be assumed the same since a manufacturer may only have information on their virgin material. This is a fair assumption when primary materials and their production are the same (e.g., high-density polyethylene pellets [HDPE] for a milk or detergent bottle). However, when they are not (e.g., some paper products) or when data are not available comparing production of a product with virgin versus recycled materials, it may be necessary to identify an alternative method to allocate recycling credits and debits.

2. **Allocate the disposal credits to the product that gets recycled** (Product 1). Product 2 then treats Product 1 as a raw material that needs to be processed (recycling inputs and outputs). In using Product 1 as a raw material, Product 2 has avoided virgin material production. Using this method, net inputs and outputs for Product 1 are as follows:

\[
N_{I/O} \text{ (Product 1)} = D - B(a)
\]
Net inputs and outputs for Product 2 are as follows:

\[ N_{I/O} \text{(Product 2)} = E - A(b) + C(a) + F \]

An advantage of this system is its utility when primary materials and their productions are different. This method may be especially useful for composted materials.

**Recommendations.** The first method, 50/50 allocation, should be used whenever possible and when data are available. However, we acknowledge that in some cases the second method may be more appropriate. In any event it is important to state clearly the method being used, to explain why it was chosen, and to be consistent in its use. More experience and research is clearly needed in this area before a particular method is exclusively recommended.

### 7.2.2.4 Coproduct Recycling

The above methodology is relevant for post-consumer or finished product recycling. For example, if 100 percent recycling occurs, 100 kg of HDPE could go from 100 kg of milk bottles to 100 kg of detergent bottles. However, with recycling of intermediate scrap, the scenario depicted in Figure 7-4 is more likely.

![Coproduct Recycling Diagram](image)

**FIGURE 7-4. COPRODUCT RECYCLING**

In this case, 1,000 kg of primary material are produced. But in converting to Product 1, 200 kg are lost. These 200 kg (which were never part of Product 1) are used to convert to Product 2. Coproduct recycling is unlike post-consumer recycling, which may involve more extensive collection and processing (i.e., cleaning) steps. This case should be treated as coproduct generation, and inputs and outputs associated with virgin material production will be allocated on the basis of weight.

### 7.2.3 Projections

When evaluating recycled content levels and recycling rates, one should always indicate what the current situation is and present information based on this. Data can then be obtained on recycling inputs and outputs at that rate and on conversion inputs and outputs at that level of recycled content. However, it is often useful to project how an increase in recycling or recycled content will affect net inputs and outputs. These data can be used in developing a plan to improve a product's environmental quality; for example, should efforts focus on recycling or source reduction? Developing projections should be encouraged, but one must acknowledge the accompanying increase in data uncertainty. Currently, projecting a recycling rate is derived from a linear extrapolation. One cannot obtain actual data since that rate is not actually being achieved; in fact it is highly likely that the relationship is nonlinear since efficiencies may change at differing recycling rates. This is an area requiring future research, and a consensus is needed on a methodology that treats all products in a consistent and fair manner.
7.2.4 Research Recommendations

Recycling technology is expected to advance greatly in the near future. This will further complicate open-loop recycling because of the number of products being recycled into similar and dissimilar products. More research is needed to decide how to fairly allocate costs associated with recycling over a wide array of possible products, including recycling options not involving consumer use (pre-consumer recycling). Another area for further research is composting. Composting is still in an embryonic stage; little information is available on end-use markets, composting inputs and outputs, and materials converted to compost. Until this information is available, developing a system to allocate composting inputs and outputs will remain difficult.

7.3 DATA SOURCES, METHODOLOGIES, AND DEFICIENCIES FOR RECYCLING INFORMATION

For recycling, the same categories of data sources are applicable as for use/re-use/maintenance (See Chapter 6). However, the availability of data on recycling activities is more limited. Also, since many life-cycle inventories incorporate projections of recycling levels far beyond those currently achieved, new issues emerge: How representative is the (limited) information available today about conditions that would prevail under higher levels of recycling? How realistic or technically achievable are those higher rates?

7.3.1 Data Sources and Availability

For some products, recycling, driven by economics, has been practiced for many years, and an infrastructure and markets for the recycled materials already exist. Data on quantities of material recovered and, to a lesser extent, products using recycled material, are available. In these cases, information on the activities required (collection, transportation, processing) as well as the inputs and outputs is available from primary and secondary sources.

Table 7-1 identifies the types of primary and secondary data sources that may be available for studies of products with an existing market for recycled material already exists. In those cases, companies in the business of recycling and reprocessing can provide information on patterns of activity (e.g., transportation distances, reprocessing steps, etc.), as well as some input and output information. In addition, secondary data often will be available on quantities re-used and recovered. However, data will not be complete. Even for products where recycling is widely practiced, complete data may not exist on the collection sources and the users of the recycled material. This problem becomes greater as the number of uses for the recycled material increases.

For products in which recovery and recycling rates are low and/or for which recycling is relatively recent, data will be much more limited. Information on the activities required for expanding recycling beyond current levels may be nonexistent, such as those associated with an infrastructure that does not currently exist. In these cases, primary data sources (i.e., sources contacting directly those parties currently involved in collection, reprocessing or using the recycled material) may be the only reliable sources of data. Nevertheless, the reasonableness of the infrastructure model proposed for such theoretical systems can be compared with existing systems and sensitivity analyses used to check the effects of variability.
TABLE 7-1. COMMON DATA SOURCES FOR COMPONENTS OF RECYCLING

<table>
<thead>
<tr>
<th>Primary</th>
<th>Secondary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curbside collection</td>
<td>End users, Municipalities,</td>
</tr>
<tr>
<td></td>
<td>Recyclers</td>
</tr>
<tr>
<td>Self transport</td>
<td>End-user patterns, Vehicle</td>
</tr>
<tr>
<td></td>
<td>manufacturers</td>
</tr>
<tr>
<td>Composting</td>
<td></td>
</tr>
<tr>
<td>• On-site</td>
<td>End-user patterns</td>
</tr>
<tr>
<td>• Off-site</td>
<td>Municipal and industrial</td>
</tr>
<tr>
<td></td>
<td>facilities</td>
</tr>
<tr>
<td>Recycling collection</td>
<td>Recycling dealers, Users of</td>
</tr>
<tr>
<td></td>
<td>recycled materials</td>
</tr>
<tr>
<td>Reprocessing</td>
<td>Reprocessors, Users of recycled materials</td>
</tr>
</tbody>
</table>

7.3.2 Forecasts and Projections

Recycling market dynamics are similar to those of other goods and services. A number of factors influence the supply of and demand for recycled materials. However, the users of reprocessed, recycled materials tend to be located in areas near manufacturing activity, whereas the source of the recycled materials is located near the end users.

When levels of recycling are very low and pilot programs predominate, the collection of recycled material and its reprocessing is relatively small in scale. Such pilot programs operate in the absence of a recycling infrastructure and activities that would be required at higher recovery rates.

Forecasting from very low levels of recycling to higher levels requires that these activities be incorporated into the analysis in a valid manner. The uncertainty surrounding data used as the basis for such projections is very large. As discussed in Sections 7.2.3 and 7.2.4, this area requires further research.

7.3.3 Results Reported

The results reported for recycling activity incorporate all the items enumerated in Chapter 6 for use/re-use/maintenance in terms of form and type of information. In addition, the underlying assumptions and the sensitivity analysis surrounding forecasts and projections should be added.
7.4 RECOMMENDATIONS AND RESEARCH
AND DEVELOPMENT NEEDS

Recommendations for Data Reporting. The reporting of results for recycling activities should incorporate all the items enumerated in Section 6.6.1 for use/re-use/maintenance in terms of form and type of information. In addition, the underlying assumptions and the sensitivity analysis surrounding forecasts and projections should be added.

Recommendations for Dealing with Data Issues. See the discussion in Section 6.6.2, which is equally applicable to recycling.

Recycling Methodology Recommendations. The first product allocation method described in Section 7.2.2.3 (i.e., 50/50 allocation) should be used whenever possible and when data are available. However, in some cases the second allocation method may be more appropriate. In any event it is important to state clearly the method being used, to explain why it was chosen, and to be consistent in its use.

Recycling Research and Development Needs. Expected advances in recycling technology will further complicate open-loop recycling because of the number of products being recycled into similar and dissimilar products. More research is needed to decide how to fairly allocate the costs of recycling over a wide array of possible products, including recycling options not involving consumer use (pre-consumer recycling). Another area for further research is composting. Little information is now available on end-use markets, on composting inputs and outputs, and on materials converted to compost. This information will be needed to develop a way of allocating inputs and outputs.

Data Research and Development Needs. Forecasting from very low levels of recycling to higher levels requires that these activities be incorporated into the analysis in a valid manner. The uncertainty surrounding data used as the basis for such projections is very large and further research is needed to develop projection methodologies.
CHAPTER 8.0

WASTE MANAGEMENT

8.1 OVERVIEW OF WASTE MANAGEMENT

This chapter describes a framework that can be applied to steps and processes to identify waste streams, describe waste management alternatives, and quantify releases to the environment. The guidelines define considerations for examining and collecting data for the inventory. No attempt has been made to list every pollutant or waste category that may be included in such an analysis. Instead a template has been developed that can be generally applied to the identification of wastes from any step.

8.1.1 Definitions and Objectives

Three definitions are important to make in the understanding of this chapter. The first two definitions are those of waste and coproduct. Basic criteria used to distinguish wastes from coproducts are conventional usage and disposal practices. Wastes are defined as materials that, usually following treatment, have no market or intrinsic value (sometimes for technical reasons) and are disposed of in the environment. Coproducts are retained for further commercial purposes, because they do have some alternative value or function. In some life-cycle stages, wastes can be created without prior treatment, e.g., rubber tire compounds during transportation.

Products and coproducts must be clearly distinguished to assign the proportions of waste and energy associated with their generation. For instance, energy and wastes associated with overall production of beef cattle should be proportioned across each coproduct (meat, leather, tallow, bone meal) to reflect environmental loadings for the production of all useful commodities. How these energy inputs and waste outputs should be proportioned for coproducts is discussed in Section 4.1.3. Life-cycle inventories have typically used either the proportional amount (mass or chemical equivalents) or the relative economic value in partitioning the inputs and outputs. Because of the dynamics of the economically based procedure, its use in life-cycle inventories is not generally recommended.

Waste releases may not always be handled under properly managed conditions; therefore the term includes both routine and accidental releases. General waste categories to be considered as appropriate in the life-cycle inventory are listed in Table 8-1.

The third key definition is that of the waste management system (WMS). Waste streams may be generated at virtually every stage of the five identified life-cycle stages. A waste management system consists of the techniques for treating or handling a waste prior to its release to the environment. A distinction may be drawn between an on-line WMS whose loadings to the environment are directly associated with the system producing the product and an off-line WMS
<table>
<thead>
<tr>
<th>I. Non-hazardous Solid Waste</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Municipal Solid Wastes</td>
</tr>
<tr>
<td>1. Residential</td>
</tr>
<tr>
<td>2. Commercial</td>
</tr>
<tr>
<td>3. Institutional</td>
</tr>
<tr>
<td>B. Municipal Sludge</td>
</tr>
<tr>
<td>1. Wastewater treatment</td>
</tr>
<tr>
<td>2. Water treatment</td>
</tr>
<tr>
<td>C. Medical Waste (hospitals, doctors, clinics, vets)</td>
</tr>
<tr>
<td>1. Regulated (red bag)</td>
</tr>
<tr>
<td>2. Unregulated (brown bag)</td>
</tr>
<tr>
<td>D. Industrial Wastes</td>
</tr>
<tr>
<td>E. Agricultural</td>
</tr>
<tr>
<td>F. Silvicultural</td>
</tr>
<tr>
<td>G. Mining</td>
</tr>
<tr>
<td>H. Construction/Demolition</td>
</tr>
<tr>
<td>I. Drilling Slurries</td>
</tr>
<tr>
<td>J. Low-level Radioactive</td>
</tr>
<tr>
<td>K. Waste Tires</td>
</tr>
<tr>
<td>L. Power Plant Ash</td>
</tr>
<tr>
<td>M. Incinerator Ash</td>
</tr>
<tr>
<td>N. Air Quality Control Device Sludges</td>
</tr>
<tr>
<td>O. Municipal Sludge Ash</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>II. Hazardous Solid Wastes</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. High-level Radioactive</td>
</tr>
<tr>
<td>B. Metallic Industrial</td>
</tr>
<tr>
<td>C. Organic Industrial</td>
</tr>
</tbody>
</table>
TABLE 8-1. (Continued)

III. Nonhazardous Liquid Wastes

A. Municipal Sewage
B. Municipal Combined Sewer Overflows
C. Waste Heat
D. Agricultural Landfill Leachate

IV. Hazardous Liquid Wastes

A. Municipal Sewage (with industrial input)
B. Mining, Tailings, Slurries

V. Air Emissions (controllable)

A. Solid Waste Incinerator (e.g. acid gases, organics, metals)
B. Hazardous Waste Incinerator
C. Sludge Incinerator
D. Fossil-fuel Power Plant
E. Nuclear Power Plant
F. Geothermal Power Plant
G. Autos, Internal Combustion Engines

VI. Emissions (uncontrolled)

A. Fugitive
   1. Grinding/Dust-producing processes
   2. Solvent application (paints, dry cleaning)
   3. Vaporization of volatiles (gasoline)
   4. Incinerators
   5. Waste/Raw Material Piles

B. Accidental
   1. Nuclear power plant
   2. Fossil-fuel power plant
   3. Incinerator upset
where the environmental loadings must be disaggregated among many systems, some of which may not contribute to producing the product of interest.

The objective of the waste management discussion is to establish guidelines for an appropriate definition of waste and to understand the nature, quantity, composition, and fate at every stage of its life cycle. Following such guidelines can serve as a tool for evaluating environmental loadings and for identifying points where opportunities for increasing efficiency and minimizing loading would have the greatest benefit. One measure of system efficiency is the quantity of waste per unit of production.

8.1.2 Waste Management Hierarchy

Within the waste management spectrum, preferences for specific techniques have been established by a variety of organizations, including many states, the U.S. Environmental Protection Agency (EPA), environmental groups, and a cross section of industries and trade associations:

- Waste minimization/waste reduction
- Re-use
- Recycling/material recovery
- Composting
- Thermal, physical, chemical, or biological treatment
- Disposal, including, e.g., land, ocean, and groundwater disposal.

Waste minimization and re-use are at the top of the hierarchy because of their relevance to multistage pollution prevention, resource conservation, and economic efficiency. Waste minimization reduces pollution by not creating it in the first place. Re-use decreases waste by minimizing new material inputs per production cycle. This occurs to a lesser degree than with waste minimization, among other reasons, because of the need for intermediate steps such as washing or sterilization. Waste minimization, re-use, and recycling lower environmental loading relative to a baseline situation are difficult to incorporate into an analysis until the baseline is developed.

The remaining waste management alternatives involve collection, processing, and ultimate disposal of waste in a management facility. These alternatives consequently generate a broad network of pollutant and resource use categories. Aside from recycling, discussed in Chapter 7, this chapter describes categories of waste releases to air, water, and land from thermal treatment with and without energy recovery, and a variety of land and water disposal methods.

8.1.3 Boundary Conditions

Waste management relates to all stages within the life-cycle inventory. Figure 8-1 depicts this relationship and indicates points of releases to the various media. The boundary of the waste management system begins where the waste is generated.
Waste management options can have strong seasonal and geographical variations, especially for municipal solid waste (MSW). Geographical variation is also a factor for hazardous wastes (plant sites, industrial states) and for mobile emissions (highways). The industrial infrastructure (and available technologies) also vary quite widely on a regional basis.

Technological controls used at waste management facilities (e.g., liners and leachate collection systems in landfills) can vary considerably from facility to facility. Because these controls can significantly affect the quantities of environmental releases, any assumption made in the life-cycle inventory regarding the control technologies used is critical and must be clearly stated. The general utility of life-cycle inventories can be limited by site-specific differences. Additional
factors that may increase the differences between average and local operations include changing waste management practices, age of equipment, distances, and local or regional emission variations.

8.2 WASTE MANAGEMENT SYSTEMS AND POTENTIAL PATHWAYS

The environmental function of a waste management system is to maximize the capture of process outputs and control the nature and rate of releases of residual wastes into specific environmental media.

8.2.1 Management Systems Overview

Generally speaking, management of wastes and ultimate residuals is accomplished by using one or more of the following generic technologies: storage, entombment, chemical modification, physical modification, biological modification, thermal treatment, and release to the environment. Specific waste technologies typically considered in the life-cycle inventory are listed in Table 8-2.

Many waste streams are combinations of materials derived from several subsystems. Allocation of the wastestream constituents to each contributing process is essential for determining how to apportion the loadings in a multiproduct process. Furthermore, the outputs of the waste management system themselves must be allocated among the various environmental media or subsequent treatment steps. This allocation may result from a physical redistribution or a more complex biological or chemical transformation within the system. As an example of the latter difficulty, a chlorine-containing waste entering an incinerator may exit as hydrochloric acid (HCl). The HCl output is directly measured as an emission rate factor and can be normalized per unit of input chlorine. The hydrogen contribution, however, may come from some other source and is not typically mass-allocated to a specific source. How one performs such allocations can significantly affect the overall accuracy and usability of a life-cycle inventory.

A variety of methods are available for performing this function of a life-cycle inventory for most physical, chemical, and biological processes. The thermodynamic models described in Chapters 2 and 4 are appropriate in instances where very specific matching of inputs and outputs is required. Emission rate factors normalized to inputs in some consistent fashion may be the only available cost-effective approach. Once a method is selected, all assumptions and quantification rationales should be described.

Table 8-3 indicates the sources of generic environmental releases. These sources should be examined in detail when evaluating any step or process of a life-cycle inventory to determine its relevance. The remainder of this section describes waste management system categories and potential release pathways to the environment.

8.2.2 Water Emissions and Wastewater Treatment

Wastewater treatment options are applied to liquid environmental releases from all stages of the product life cycle.

8.2.2.1 Definition and Concept

Such treatment systems can always be thought of as either converting the wastewater constituents into more stable (and usually less environmentally harmful) materials or concentrating
TABLE 8-2. CATEGORIES OF WASTE MANAGEMENT TECHNOLOGIES

I. Solid Wastes (Hazardous and Non-Hazardous)
   A. Incineration with energy/materials recovery
   B. Incineration (without energy/materials recovery)
   C. Vitrification
   D. Fixation/Cementation
   E. Landfilling
   F. Autoclaving, Microwaving
   G. Mechanical Shredding, Sorting, Sizing
   H. Hand-Sorting, recycling
   I. Windrow Composting
   J. In-Vessel Composting
   K. Static Pile Composting
   L. Landspreading
   M. Re-use (ash, consumer products pre MSW, medwaste)
   N. Short-term, Long-term storage
   O. Illegal Dumping

II. Liquid Wastes (Hazardous and Non-hazardous)
   A. Sewage Treatment Plant (Primary, Secondary, Tertiary)
   B. Incineration (with/without heat recovery)
   C. Underground Injection
   D. Lagoon
   E. Legal and Illegal Discharges
   F. Short and Long-term Storage
   G. Settling of solids/separation of different specific gravity liquids for recycling/re-use
   H. Filtering

III. Air Emissions (all kinds)
   A. Dust Collectors, (ESP, Baghouse, Cyclone)
   B. Scrubbers (Wet, Semi-Dry, Dry)
   C. De-NO_x (SCR, NSCR, FGR, Combustion modification)
   D. Fuel Cleaning Measures (separation, reduction)
   E. Activated Carbon Filtering
   F. Activated Carbon Injection
   G. Condensation (Humidification, Heat Exchanger)
   H. Efficient Combustion with afterburner, aux fuel, auto combustion control
them so that separation from the liquid can occur. Wastewater treatment also includes handling the solids for further processing or disposal.

Wastewater treatment options typically are not linear operational chains, but are connected cycles in which intermediate byproducts may be generated. These materials may be recycled on-site so that they never become wastes, or may be sent off-site. Materials sent off-site may or may not have some beneficial use. Thus, life-cycle inventories must very carefully track and account for these flows.

### 8.2.2.2 Pathways and Environmental Releases

Figure 8-2 is a flow chart for a generalized wastewater treatment unit. This represents only one example of how to look at one part of releases to water. From a traditional engineering process mass balance standpoint, system inputs include energy (electrical, mechanical or thermal), chemicals, and of course, the wastewater itself. For the purpose of life-cycle inventories, however, the range of input considerations and their associated second generation wastes additionally may include the following:

- **Land Use**—The land area associated with the wastewater treatment unit and, where appropriate, the area affected by collection piping and conveyance system represents a resource input to the system. Furthermore, any secondary emissions associated with the construction of the treatment and conveyance system are a part of the land use inputs.
• Maintenance Equipment and Materials—On a product-normalized basis, the equipment and materials used by the facility to maintain its functional or aesthetic performance should be allocated as inputs to the product. Such allocation should be done over the expected actual lifetime of the facility. Such equipment and materials include those internal to the treatment unit, such as lubricants for pumps, as well as external resources such as paint.

The wastewater treatment unit produces as outputs a variety of releases. These emissions can be deliberate and continuous as in the residual suspended and dissolved waterborne contaminants in the treated wastewater, intermittent as in the case of leaks, or completely accidental. Environmental releases to the atmosphere include both primary (direct) and secondary emissions in the form of volatile organic compounds (VOCs), aerosols, odors, water vapor, and heat from chemical storage tanks, process tanks, air strippers, and digesters. Secondary releases such as VOC emissions from regeneration of process media should also be included. Releases to water include the entire range of salts, metals, organic compounds, and microorganisms not removed in the treatment process. A sample listing of such materials is shown in Table 8-4.

In addition, releases may include heat and process chemicals or wastewater itself from spills, leaks, or overflows. Among potential releases to the land pathway, those consisting of byproducts having beneficial uses must be distinguished from those having no environmental benefits.

Solid waste emissions include both primary and secondary sources, and all possibilities for generating either type should be included. An example of the former category is a sludge generated directly as a result of the wastewater treatment. The latter group includes disposal of spent solids,
### TABLE 8-4. TYPICAL EMISSIONS FROM WASTEWATER TREATMENT

<table>
<thead>
<tr>
<th>Pb ions</th>
<th>CN⁻</th>
<th>Hydrocarbons (immiscible organics)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe ions</td>
<td>F</td>
<td>Chlorine, chloride</td>
</tr>
<tr>
<td>Hg₂⁺</td>
<td>S²⁻</td>
<td>Phenol</td>
</tr>
<tr>
<td>Other metal ions*</td>
<td>Dissolved organics*</td>
<td>Dissolved solids*</td>
</tr>
<tr>
<td>NH⁺</td>
<td>Suspended solids*</td>
<td>Phosphate</td>
</tr>
<tr>
<td>H⁺</td>
<td>Detergents, oils*</td>
<td>Other (nitrogen)*</td>
</tr>
<tr>
<td>NO₃⁻</td>
<td>BOD and COD**</td>
<td>Coliform</td>
</tr>
</tbody>
</table>

* Marked items can and should be further subdivided, if possible and if consistent with data.
** Some care is needed with BOD. Some workers report BOD₃, some BOD₇, and some BOD₉, where the numeric subscript refers to the duration of the test in days.

such as ion exchange resins. Byproducts having beneficial uses include regenerable treatment chemicals, e.g., reclaimed lime sludge and biological sludges with nutrient and organic content.

Credits for either reduction of raw materials or replacement of alternative products (such as chemical fertilizers) should be applied to the weight of waste generated. Such credits should be calculated on a mass replacement basis for the specific constituents. Nonreplaced constituents, heavy metals for example, would be accounted for in total only if they represent a statistically significant fraction. However, in all cases, their presence must be acknowledged.

In summary, wastewater management options create complex primary and secondary pathways from the source of the wastewater to air, water, and land (Table 8-5). Life-cycle inventories must account for these complexities in a comprehensive and consistent fashion. In particular, materials or energy moving from the wastewater treatment system into other systems or into the environment may describe a highly complex cycle. The use of wastewater heat or energy recovery in a process versus dissipation in a heat exchanger, for instance, necessitates a very rigorous application of systems engineering concepts to avoid either a gap in counting or double-counting.

### 8.2.3 Air Emissions and Air Pollution Control Systems

Air emissions result from nearly every life-cycle stage and may or may not pass through some type of air emission control device or be otherwise regulated or measured.

#### 8.2.3.1 Definition and Concept

The pathways and mechanisms of air emissions are described generically in Figure 8-3. Following that are listings of what are included in each part of the chart. These listings are not intended to be complete, but rather exemplify what should be considered in the development of the life-cycle inventory.
### TABLE 8-5. POTENTIAL PATHWAYS FROM WASTEWATER TREATMENT

<table>
<thead>
<tr>
<th>Media</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Air</td>
</tr>
<tr>
<td>Primary</td>
<td>Water</td>
</tr>
<tr>
<td>Primary</td>
<td>Land</td>
</tr>
<tr>
<td>Secondary</td>
<td>Air</td>
</tr>
<tr>
<td>Secondary</td>
<td>Water</td>
</tr>
<tr>
<td>Secondary</td>
<td>Land</td>
</tr>
</tbody>
</table>

#### FIGURE 8-3. POTENTIAL AIR RELEASE PATHWAYS

- Process
- Uncontrolled Release to Air: Gaseous, Aerosol, Solid
- Air Pollution Control Equipment
- All Releases to Air: Gaseous, Aerosol, Solid
- Solid and Liquid Wastes, Spent Media
- Waste Management and Material Recovery System (also a Process)
The boundaries drawn in this chart are not intended to be rigid. Boundaries for the waste management system depend on the definition of a waste, and this can vary with legal, economic, technical, and geographical considerations. In general, however, the following discharges are considered air emissions:

- Those resulting from any process that does not pass through any type of control system
- Those from a control system, including those resulting from equipment malfunction
- Those from a waste management system.

Air pollution control systems tend to be relatively linear, given the flow of airborne materials through a system. Air emissions also tend to be easier to characterize than those for other media, since they are usually molecular gases or air suspensions of fine solids or aerosols.

### 8.2.3.2 Pathways and Environmental Releases

It is essential to identify both direct and indirect air emissions from each process step to evaluate the environmental loading and identify opportunities for improvements (Table 8-6). For example, the natural gas distribution system is thought to suffer losses in the range of 3 to 12 percent. This is significant not only to account for energy and nonrenewable resource loss, but also because methane is a major greenhouse gas.

Air emissions may have primary and subsidiary effects. Inhalation and deposition are examples of possible direct pathways of environmental releases to animals and plants which may cause effects. Other possible direct effects include greenhouse warming, ozone depletion or generation, and acid rain formation. Secondary and tertiary effects arise when air emissions are deposited in soil and water and enter the food chain or other metabolic and biological pathways.

A possible classification or categorization scheme for these materials would be by their status as criteria or noncriteria pollutants. Currently, these data are not systematically collected and compiled other than what is needed for permit purposes. The most comprehensive list of air emissions could be developed either from direct contacts with facilities or from current federal and state permit and reporting requirements for each type of process and release pathway.

Research needs include:

- Compile a comprehensive list of pollutant and emission categories from current federal, state, and local permit and reporting requirements
- Develop consistent standards to fill gaps in current requirements, to standardize measurement and reporting requirements, and to minimize the incentive to take advantage of localities with less stringent reporting and regulation
- Develop standard measurement methods and technologies.
TABLE 8-6. CHARACTERIZATION OF CONTROLLED AND UNCONTROLLED EMISSIONS TO AIR

<table>
<thead>
<tr>
<th>Physical state</th>
<th>Gaseous</th>
<th>Particulate, solid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vapor, aerosol</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chemical properties</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>VOC</td>
<td>CFC</td>
<td>HC</td>
</tr>
<tr>
<td>NO&lt;sub&gt;x&lt;/sub&gt;</td>
<td>SO&lt;sub&gt;x&lt;/sub&gt;</td>
<td>Hg</td>
</tr>
<tr>
<td>Pb</td>
<td>Other metals</td>
<td>pH</td>
</tr>
<tr>
<td>Low-level radionuclides</td>
<td>CO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>CO</td>
</tr>
<tr>
<td>CH&lt;sub&gt;4&lt;/sub&gt;</td>
<td>HCl</td>
<td>Cl&lt;sub&gt;2&lt;/sub&gt;</td>
</tr>
<tr>
<td>HF/F-</td>
<td>CHO (aldehydes, ketones)*</td>
<td>CN</td>
</tr>
<tr>
<td>Dioxins, furans*</td>
<td>H&lt;sub&gt;x&lt;/sub&gt;S</td>
<td>Mercaptans*</td>
</tr>
<tr>
<td>NH&lt;sub&gt;3&lt;/sub&gt;</td>
<td>Halon</td>
<td>Hydrocarbons*</td>
</tr>
<tr>
<td>Other organics*</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Marked items can be further subdivided if necessary.

Note 1: There is no simple way of combining these into any sensible, meaningful categories.

Note 2: The oxides of carbon arise mainly from the combustion of fuels. The carbon content of most fuels is known with some accuracy, so the total carbon in CO and CO<sub>2</sub> can be checked against fuel input.

Note 3: SO<sub>x</sub> arises predominantly from impurities in fuels, with the exception of sulfide ore smelting.

8.2.4 Thermal Waste Treatment Technologies

Thermal treatment of wastes includes incineration devices and an array of emerging thermal technologies, including pyrolysis and vitrification.

8.2.4.1 Definition and Concept

A schematic block diagram for a generic waste incinerator is shown in Figure 8-4. The input waste stream may be municipal solid waste, MSW sludge, hazardous waste, medical waste, or other sludges. The diagram also shows the associated pollution control device(s), such as a wet/dry scrubber and electrostatic precipitator (ESP). Energy in the form of heat or electricity may or may not be exported from the process. In general, an incineration train will exhibit virtually all the environmental effects of any complex industrial power train; these might include noise, odors, aesthetic, ecological, and other environmental loadings. The composition and toxicity of the atmospheric discharges and solid combustion residues (ash) have been major public and technical issues.
8.2.4.2 Pathways and Environmental Releases

Air emissions from incinerators include, but are not limited to, the following constituents:

- CO$_2$ and H$_2$O
- Criteria pollutants
- Products of incomplete combustion (PICs) and particulate organic chemicals (POCs)
- Heavy metals
- Dioxins and furans
- Waste heat.

A priori prediction of the constituents of atmospheric discharges from incinerators is of extraordinary complexity, although some idealized estimates are possible. The latter include the equilibrium and stoichiometric estimating methods discussed in Chapter 4. Prediction of PICs and POCs is confounded by the turbulent and heterogeneous nature of incinerator combustion. Extreme care must be exercised in using empirical databases to estimate PICs and POCs because of turbulence-scaling difficulties.
Additional uncertainties in the operation of incinerators relevant to life-cycle inventory accuracy and interpretation include:

- Heavy metals partitioning between fly ash, bottom ash, and emissions
- Apportionment of releases to be ascribed to one component of a mixed feed stream
- Mechanism of dioxin or furan formation
- Effect of chlorine content of waste
- Mechanism for free halogen formation
- Basis for energy credits
- Effects of ash use
- Ash stabilization/solidification system releases
- Effects of waste composition changes and consequent allocation and apportionment issues
- Fugitive emissions
- Frequency, duration, and amount of waste from upsets and dump stacks
- Combustion of halogen containing materials
- Development of generic databases for atmospheric discharges
- CO$_2$ and NO$_x$ emissions
- Acid gas formation and acid rain
- Ultimate fate of sulfur, phosphorus, nitrogen, and heavy metals.

The environmental impacts of incinerators also include those of land disposal of the residuals. The latter are enumerated further in this chapter.

8.2.5 Land Disposal

8.2.5.1 Definition and Concept

Land disposal of waste includes all wastes generated at all phases in a product life cycle and discharged to a nondedicated waste management system that ultimately resides on or in the land upon disposal. This definition includes, but is not limited to:

- Sanitary landfills
- Limited purpose landfills
- Land spreading
- Well injection
- Composting
- Uncontrolled disposal, such as illegal dumping and litter.

Land-based disposal is a common, primary waste management practice. Land disposal is highly visible and is frequently subjected to considerable public policy review. Also, land disposal has substantial consequences in terms of both controlled and uncontrolled releases to the environment.

8.2.5.2 Pathways and Environmental Releases

A generalized mass/energy flow model for land disposal is shown in Figure 8-5. In the generalized flow model, two flows, wastes and energy, cross the system boundary into the land disposal system. Wastes cross into the land disposal system from all phases identified within a life-cycle inventory, as well as from intermediate waste management processes. Examples of solid wastes include glass containers, paperboard containers, cans, and plastics. Energy flows into the system include, but are not limited to, energy used by waste-handling equipment (excluding transport energy) and energy used by equipment or processes necessary to mitigate releases.

![FIGURE 8-5. GENERALIZED MASS/ENERGY FLOW MODEL FOR LAND DISPOSAL](image)

Flows out of the system include:

- Airborne emissions
- Land emissions
- Water emissions
• Energy releases
• Fugitive emissions.

*Airborne emissions* may include, but are not limited to:

• Methane and other gas formation and release
• Waste handling equipment emissions
• Volatilization of liquid wastes
• Emissions from landfill gas combustion and energy production.

*Land emissions* may include, but are not limited to:

• Chemicals applied to soils
• Municipal sludge applied to soils
• Application of compost.

*Water emissions* may include, but are not limited to:

• Groundwater releases and contamination
• Surface water runoff
• Leachate production and treatment processes
• Soil erosion
• Nonpoint source emissions.

*Energy releases* may include, but are not limited to:

• Waste heat
• Landfill gas combustion and energy production.
**Fugitive emissions** may include, but are not limited to:

- Litter
- Spills and other accidental releases of wastes
- Containment failures
- Waste handling equipment malfunctions.

### 8.2.5.3 Uncertainty and Research Needs

Several areas of uncertainty exist for land disposal. These include, but are not limited to:

- Partitioning air and water emissions by product or waste type
- Leachate formation mechanisms
- Disposal site ecosystem interactions
- Liner design life integrity
- Local disposal site ecological impacts (i.e., birds, vectors, plant life, etc.)
- Decomposition daughter products
- Disposal implications from land application of waste and waste-derived products.

Areas of critical research need include:

- Fundamental understanding of leachate generation and mobilization
- Long-term landfill liner integrity studies
- Fundamental understanding of landfill gas generation, including both long-term gas production stability and energy production credits
- Fundamental understanding of the origin of trace toxics
- Fundamental understanding of the role of methane generated by land disposal with respect to global warming
- Quantification of the environmental effects associated with waste composting, including MSW composting, hazardous waste composting, and bioremediation via composting
- Consequences of reducing landfill water content.
8.2.6 Aquatic Release Pathways

Aquatic pollution pathways are highly variable and, in some cases, not obvious without careful consideration of the entire producing network. Pathways to aquatic environments are illustrated in Figure 8-6. Emissions can be derived directly or indirectly from either land-based process activities that affect lakes and streams or by ocean- or estuarine-based activities. Activities occurring in the marine environment include marine components of cycles that are primarily land based such as off-shore oil production, as well as those that are primarily marine focused such as fishing.

**FIGURE 8-6. POTENTIAL AQUATIC RELEASE PATHWAYS**

Land-based processes may lead to aquatic release pathways in six ways:

- **Atmospheric Deposition**—Particulate and gaseous emissions from processes occurring on land may be deposited on the surface of water bodies

- **Nonpoint Sources**—Runoff from areas adjacent to water bodies

- **Liquid Waste Treatment Byproducts**—Effluents may reach surface waters through discharge pipes (point sources), either continuously as a result of liquid waste treatment operations along the shore or intermittently from combined sewer overflows
• **Sludges**—Solid or slurry byproducts that are either piped into inland or nearshore waters or barged offshore

• **Solid Waste**—Products lost during manufacturing or distribution

• **Littering**—Post-consumer product or packaging that ends up in aquatic systems.

Freshwater, estuarine, and marine activities include such physical releases as air emissions redeposited on the water surface and aquatic resource modifications such as habitat alteration. Spills from on-water accidents also should be quantified in this category.

**Assumptions.** A considerable number of assumptions may be required to estimate aquatic release pathways. These include:

- Transport and deposited quantities resulting from land- or water-based processes
- Quantities of product losses to aquatic systems, either direct or indirect (litter)
- Extent of shoreline and underwater habitat modification.

**Uncertainties and Research and Development Needs.** The primary needs are methods by which to estimate accurately indirect releases.

### 8.3 DATA COLLECTION AND REPORTING

A series of building blocks will be used to develop a comprehensive picture of waste generation. Airborne, waterborne, and solid wastes will be analyzed independently, recognizing (a) that many processes will generate all three types of waste and (b) that a waste management process may reduce wastes in one category while increasing wastes in another category.

#### 8.3.1 General Procedure

Each stage of a product's life cycle (raw materials acquisition, processing/manufacturing/formulation, distribution and transportation, use/re-use/maintenance, recycling and waste disposal) can be broken into smaller process steps. The air, water, and solid wastes generated from each of these smaller steps can then be analyzed. Once such data have been generated for each small step, they can be aggregated and a table of wastes generated for each phase of the life cycle can be developed. Finally, a summary table for a specific product or activity can be aggregated from the more detailed tables. Tables 8-7 through 8-11 illustrate this procedure. The final two columns of Tables 8-7, 8-8, and 8-9 are not an essential component of the baseline inventory, but may provide useful information if the life-cycle assessment includes an improvement analysis.

Separately presenting data for wastes generated at different life-cycle phases is advantageous in identifying particular systems and subsystems where the wastes are generated and in identifying opportunities for waste prevention or minimization. Minimization potential will also be highlighted in an improvement assessment by including a description of potential waste control measures and the expected reduction in the amount of waste released if such measures were adopted.
### TABLE 8-7. SAMPLE AIRBORNE EMISSIONS BY GENERIC PRODUCTION UNIT

<table>
<thead>
<tr>
<th>Release Type</th>
<th>Emissions Source</th>
<th>Emissions Category</th>
<th>Current Management Practice</th>
<th>Amounts (Range or Deviation)</th>
<th>Optional Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point Sources</td>
<td>Incinerator</td>
<td>Non-criteria</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CO2</td>
<td>None</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>NAAQS</td>
<td>Quantitative</td>
<td>(x kg) or Qualitative</td>
<td>(x-y)kg</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Scrubber</td>
<td>&quot;expected to be present&quot;</td>
<td></td>
</tr>
<tr>
<td>HAPS</td>
<td></td>
<td></td>
<td>Absorber</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SARA Title 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fugitive</td>
<td>Municipal Solid</td>
<td>Waste-Landfill</td>
<td>Explosion</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**ROUTINE RELEASES**

**ACCIDENTAL RELEASES**

Note: In view of the unique environmental properties of each pollutant, it is **not** acceptable to sum the quantities of different pollutants.
TABLE 8-8. SAMPLE WATERBORNE EMISSIONS BY GENERIC PRODUCTION UNIT

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Point</td>
<td>Activated Sludge Wastemaker Treatment</td>
<td>Clean Water Act Priority Pollutants</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-Point</td>
<td>Primary Drinking Water Standards Ambient Water Quality Criteria</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accidental</td>
<td>SARA 313</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: In view of the unique environmental properties of each pollutant, it is not acceptable to sum the quantities of different pollutants.
### TABLE 8-9. SOLID WASTE LOADINGS BY GENERIC PRODUCTION UNIT

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Routine</td>
<td>Landfill</td>
<td>Municipal Non-Hazardous</td>
<td></td>
<td></td>
<td></td>
<td>Light weighting (x-y) kg (a-b) m³</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-plastics</td>
<td>x kg</td>
<td>x kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>-paper</td>
<td>a m³ (actual disposal volume)</td>
<td>a m³ (actual disposal volume)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hazardous</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Infectious</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radioactive</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accidental</td>
<td>Municipal Sludge</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: In view of the unique environmental properties of each pollutant, it is not acceptable to sum the quantities of different pollutants.
TABLE 8-10. SAMPLE FORMAT FOR GENERIC PRODUCTION UNIT: ENVIRONMENTAL RELEASES, SUMMARY TABLE

<table>
<thead>
<tr>
<th>Release</th>
<th>Total Amount (kg or m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Airborne Waste</strong></td>
<td></td>
</tr>
<tr>
<td>Noncriteria releases</td>
<td></td>
</tr>
<tr>
<td>--</td>
<td>X kg</td>
</tr>
<tr>
<td>NAAQS</td>
<td></td>
</tr>
<tr>
<td>HAPS:</td>
<td></td>
</tr>
<tr>
<td>• Benzene</td>
<td></td>
</tr>
<tr>
<td><strong>Waterborne Waste</strong></td>
<td></td>
</tr>
<tr>
<td>Nonregulated waste</td>
<td></td>
</tr>
<tr>
<td>Ambient water quality pollutants:</td>
<td></td>
</tr>
<tr>
<td>• COD</td>
<td></td>
</tr>
<tr>
<td>• Individual pollutants</td>
<td>Y kg</td>
</tr>
<tr>
<td>Priority pollutants:</td>
<td></td>
</tr>
<tr>
<td>• Benzene</td>
<td></td>
</tr>
<tr>
<td>Primary drinking water standards</td>
<td></td>
</tr>
<tr>
<td><strong>Solid Waste</strong></td>
<td></td>
</tr>
<tr>
<td>Nonhazardous industrial</td>
<td>kg and m³</td>
</tr>
<tr>
<td>Hazardous</td>
<td></td>
</tr>
<tr>
<td>Municipal solid waste</td>
<td></td>
</tr>
<tr>
<td>Infectious</td>
<td></td>
</tr>
<tr>
<td>Municipal Sludge</td>
<td></td>
</tr>
<tr>
<td>Mining waste</td>
<td></td>
</tr>
</tbody>
</table>

Note: In view of the unique environmental properties of each pollutant, it is not acceptable to sum the quantities of different pollutants.

of the U.S. EPA regulatory categories is one option to provide a framework for listing pollutants. An example of such a compilation is given in Table 8-11.

A summation and rearrangement of data are developed and presented in Tables 8-7 through 8-10. The emissions to each medium (air, water, solid) are listed by pollutant within the appropriate
### TABLE 8-11. TOTAL RELEASES FOR THE LIFE-CYCLE INVENTORY COMPONENT

<table>
<thead>
<tr>
<th>Release</th>
<th>Amount</th>
<th>Environmental Relevance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Airborne Waste</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nonregulated:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- CO₂</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- SO₂</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regulated:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Conventional</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- SS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- COD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Toxic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Carcinogenic</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Waterborne Waste</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nonregulated:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- SS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- COD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- BOD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regulated:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Conventional</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- SS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- COD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Toxic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Carcinogenic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Benzene</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Solid Waste</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nonhazardous</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Municipal Waste</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Municipal Sludge</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hazardous Waste</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: In view of the unique environmental properties of each pollutant, it is not acceptable to sum the quantities of different pollutants.
categories. Thus, while benzene may appear many times in Table 8-7 because it is released from a number of sources within some processes, it will appear only once in Table 8-10 because all of those airborne benzene releases from this process are summed.

The broadest summary is presented in Table 8-11. The presentation of data by pollutant within categories is similar to that in Table 8-10, but the total amount of that pollutant across an entire phase of the life cycle is presented. In addition, environmental relevance is listed. Tables similar to Table 8-11 could be developed which continue to aggregate the data across the life-cycle phases, so long as the different media phases (air, water and solid waste) and the individual pollutants were kept distinct.

8.4 UNCERTAINTIES AND RESEARCH RECOMMENDATIONS

8.4.1 Checklist of Waste Sources and Pollutants

Development of a standardized list of potential release pathways and waste sources would help to ensure that items not commonly considered, but potentially significant, are included in the analysis. Development of a standardized list of chemicals and pollutants (possibly grouped by regulatory categories) would help to ensure that all relevant pollutants are accounted for. Heat and microbial contaminants, as well as chemicals, should be listed. In addition, some unregulated loadings such as CO$_2$ belong on the list.

8.4.2 Material Residence Time in Relation to Product Output (Time Lags)

Output streams with different residence times occur in several waste treatment techniques. An example is the different residence time for the water and sludge flow during sewage treatment. The measured concentration in the water at any instant reflects the influent concentration a few minutes to hours earlier, whereas sludge concentration is averaged over many days or weeks. One must be careful that these long-term averages reflect the actual output of the system only during the period when the input of interest existed. If a sludge residence time of two weeks exists for a system and the product of interest for a life-cycle inventory is released only one week per month, then at a single point in time, the quality of the sludge may reflect nonrelevant inputs before and/or after the key period. More samples and additional data interpretation methods are needed to ensure the quality of data in such instances.

Adsorbable chemicals (those that adhere to various surfaces) will have an average residence time between the hydraulic and the sludge residence times. More research is needed to assess how the material residence time affects partitioning of the material among the different media. Time lags between the releases of waste materials should also be taken into account, such as in the case of delayed discharge of sludge from sludge lagoon treatment.

8.4.3 Aggregation of Data Input

Data in existing life-cycle inventories are sometimes reported in an aggregated form, such as by listing all VOCs together or by listing all halogen containing materials as a group. It must be recognized, however, that individual chemicals in such groups can have very different environmental properties. An adequate interpretation of these chemicals in the context of a life-cycle inventory
requires that such an aggregation is not done, but that chemicals are listed individually. If the available data do not allow individual listing, this fact must be explained.

### 8.4.4 Accuracy of Data Input

Various waste streams are characterized by measuring the concentrations of chemicals or of conventional parameters (COD, BOD, etc.) by analytical means. When this is done, the analytical methods used have to be reported. The variability of the measured data has to be taken into account, such as by listing the range of concentrations, minimum and maximum values, or a computed statistical deviation from the mean. In a number of cases, actual data will not be available for the volume of some emissions from waste treatment units. Sometimes it is theoretically possible to estimate the partitioning of a compound between the different media (air, water, solid waste). When such estimates are made, assumptions and calculations have to be reported. The sensitivity of the life-cycle inventory output to changes in this estimation has to be explained, when uncertainty exists about the accuracy of the estimation.

### 8.4.5 Monitoring and Reporting Pollutants

A more complete list of pollutants than is currently characterized in a life-cycle inventory would be helpful; however, data are not available for many of the suggested pollutants.

### 8.4.6 Allocating Environmental Releases to Incoming Waste Streams

A life-cycle inventory often requires that the energy requirements and environmental loadings are allocated proportionally to the various components of the incoming waste streams. This allocation could be based on a variety of parameters, such as weight, volume, oxygen demand, or electrochemical equivalent. The allocation factors used for the various treatment types and the implications of this choice on the study results should be explained in the study report. Although mass is recommended as the simplest allocation technique, research is needed to determine in which circumstances alternative ways to allocate the various environmental releases to the individual incoming waste streams are appropriate or essential.

### 8.4.7 Partitioning

The life-cycle inventory should provide information on environmental releases to all media from all waste management methods. For example, benzene in a sludge waste can be measured; however, determining the amount of benzene that is released to the air or water after that sludge is placed in a lagoon may not be possible without actual monitoring data. Better models and monitoring methods are necessary to develop accurate release estimates.

### 8.4.8 Environmental and Health Relevance

Information on the environmental and health significance of pollutants is needed. Where data are insufficient, further research is needed to assess the effects of particular pollutants. For further information on any one particular waste management system, refer to Section 8.2.
Research needs to enhance the methods to perform life-cycle inventories are presented and discussed below. These research needs were developed from the specific areas where the workshop participants believe additional research would improve the methods to perform life-cycle inventories and their application. Some of the research needs represent more long-term efforts; others could be resolvable immediately through acquisition and interpretation of available data. Individual research needs were characterized into two broad categories, database development and inventory methodology refinements.

9.1 DATABASE DEVELOPMENT

Development of data-quality standards. Because life-cycle inventories are very data-intensive and data quality can affect the outcome of an inventory, the development of uniform criteria for selection and reporting of data sources and types is crucial. Some basic acceptable standards for data quality should be developed. Considerations should include age (because the technology upon which data are based can become obsolete), frequency of data collection (ensuring that seasonal or other variability in the system is properly captured), and representativeness (inclusion of all of the mix of activities that may contribute to an environmental loading). In addition, more traditional indices of data quality (accuracy, precision, detection limits, and so forth) should be evaluated with regard to life-cycle inventory applications.

Development of generic databases and guidelines on when and how they should be used. The general recommendation was that product-, process-, or activity-specific primary data should be used whenever possible. However, severe budget constraints or the sheer number of data items may preclude primary data collection in some instances, and it will be useful to develop, validate, and maintain generic databases. Generic databases can also reduce reliance on manufacturer's proprietary data. Based on the intended use of the life-cycle inventory, specifications for the nature and quality of generic data are needed. These may represent simply an acceptable method of industry averaging or a more extensive system.

Evaluation on how industry average data should be used in life-cycle inventories. Most industry categories have developed industry-specific data, often presented as average values. However, each industry category can have a variety of plant-specific data that may differ greatly from an industry average value. Research is needed on how and when industry-average data should be used in life-cycle inventories. One consideration is that industry-average data should be based on data collected from a reasonable and representative number of plants. The time, cost, complexity, and range of processes used to make one product can also influence when industry-average versus plant-specific data are used.
Development of additional databases. The usefulness of a life-cycle inventory is enhanced greatly by the adequacy and completeness of the data. It is recommended that additional databases be specifically developed and maintained on topics such as transportation vehicle emissions, energy utilization, and accident magnitude and frequency. As discussed above, it is important to include data from a representative number of activities in order to have a quantitative estimate of the minimum and maximum values and central tendency. As part of this research and database development, additional research is needed to standardize organization, documentation, units, and other parameters.

9.2 INVENTORY METHODOLOGY REFINEMENT

Criteria and applications guidance are needed to determine what level of input and output data is meaningful. The potential number of data items for raw material and energy inputs and environmental outputs can be overwhelming. Often it is necessary to extend the analysis of inputs and outputs beyond the first level to the second or even multiple levels to identify significant contributions. Research is needed to define criteria for determining what is significant and to establish how these criteria should be applied. Case studies could be developed to show the relative magnitudes of contributions from various levels; these then could assist the life-cycle inventory analyst in anticipating implications to the study.

Establishment of a standard list of waste sources and pollutants. Although the workshop participants agreed that the final list of pollutants to be included may differ based on the product, process, or activity being analyzed, it was recommended that a standard list of chemicals and pollutants be developed. Also, a list of potential release pathways and waste sources should be developed. These checklists would help to ensure that items not commonly considered, but potentially significant, would not be overlooked in the analysis.

Generic models should be developed. Although generic models should be used with caution, they have a high potential utility in a wide variety of life-cycle inventory applications with products, processes, or activities. Such generic models could be included in modules accessible via a software system for use with relatively simple life cycles or with certain life-cycle stages, such as raw material acquisition and transportation. Generic models can encourage the development of standard approaches to life-cycle inventories, reduce duplication of effort, and reduce life-cycle inventory costs.

Development of approaches to allocate inputs and outputs among coproducts. Often during the life cycle of a product of interest, a second or even multiple products are produced. Currently, the only scientifically valid approach to allocating energy and raw material usage and environmental releases among these products is to perform complete life-cycle inventories on each one. Except for very simple products needing minimal effort to perform such additional work, the effort to define completely all systems is prohibitive. Research and case studies are needed to enhance our understanding of this allocation process and to develop approaches for allocation that are simpler, less information intensive, and accepted as uniform assumption procedures.

Approaches to allocate energy and environmental releases to all environmental media from incoming waste streams should be developed. A life-cycle inventory often requires that the energy use and environmental loadings are allocated proportionally to the various components of the incoming waste streams. Although mass is recommended as the simplest allocation technique, research is needed to determine in which circumstances alternative ways to allocate the various environmental releases to the individual incoming waste streams are appropriate. On the output side,
the allocation of emissions from a given input stream to a particular medium is not well understood. Since typical emission measurements do not relate the rate of discharge of a specific component to an input source, better methods and monitoring tools are needed to estimate allocation of source inputs and subsequent internal physical, chemical, and biological transformations to outputs into all environmental media.

**Approaches are needed which incorporate data variability.** Characterization of waste streams and raw materials is often accomplished by measuring the concentration of chemicals or conventional parameters by analytical means. As a result, information exists on the analytical method and estimate of the actual variability of the measured data. Research and case studies are needed to specify more completely how to incorporate data variability into estimates of environmental releases and to develop a better understanding of the implications to the final results of such variability.

**Development of approaches to incorporate sensitivity analysis into life-cycle inventory methodology.** Often obtaining detailed primary data on all subsystems along a product life cycle is not possible. In these instances secondary data or professional judgment must be used. Whether changes or uncertainty in the data will significantly affect the final results is generally unknown. Research should be performed to determine how best to incorporate sensitivity analysis or other formal error-bounding methods into life-cycle inventories and how to incorporate sensitivity analysis into data interpretation. This will provide information on how the overall product profile might vary with uncertainties in the system itself.

**Establishment of a peer review process.** For life-cycle inventories intended for external release, it is recommended that procedures for peer review be developed. The review should address methods, data sources, analyses, and interpretation. For life-cycle inventories intended for internal use, formal peer review would be optional. The peer-review process developed should allow maintenance, where necessary, of proprietary information through use of appropriate confidentiality disclosure agreements.

**Standardization of life-cycle inventory methods.** The ability to standardize the life-cycle inventories and potentially the life-cycle assessment process requires study. As in all technical work, a degree of flexibility to accommodate unique situations and to encourage innovation is needed. However, formal standardization can be helpful in increasing the efficiency of conducting the work, as well as the quality and credibility of the resulting report. A standards document could be prepared informally or in a more formal way by organizations that specialize in standardization such as ASTM. These organizations produce consensus standards. The ASTM process is open to all and a balance is sought between producers (e.g., manufacturers), users (e.g., regulators), and the public (e.g., environmental public interest groups). ASTM procedures require frequent updating of a standard, which can range from general guidelines to "cookbook" protocols.

**Development of effective approaches for communicating life-cycle inventory results.** For life-cycle inventories intended for external release, approaches are needed to communicate study methodology, findings, and limitations in a technically sound and effective manner. This is particularly important for executive summaries of life-cycle inventories which are disseminated to a broader audience that may be unfamiliar with the methodological complexities inherent in studies. Use of peer review and focus group mechanisms may be useful in determining how the public understands and interprets life-cycle inventory information.
CHAPTER 10.0

BEYOND THE INVENTORY:
Setting the Stage for the Environmental Impacts and Improvement Analyses Components of a Life-Cycle Assessment

As introduced in Chapter 1, a life-cycle assessment is not complete without also undertaking two additional analyses which are considered components of a life-cycle assessment:

• *Life-Cycle Impact Analysis*—A characterization and assessment of effects associated with a product, process, or activity. The assessment, which may be quantitative and/or qualitative, should address effects such as environmental and health considerations, habitat modification, noise pollution, socioeconomic impacts, and other impacts.

• *Life-Cycle Improvement Analysis*—A systematic evaluation of opportunities to reduce the energy, raw materials, and environmental burden associated with a product, process, or activity. Analysis may include both quantitative and qualitative measures of improvements such as changes in product or process design, reductions in raw material or energy usage, or reduction in outputs with an adverse impact on the environment.

Energy improvement optimizations should consider the total life-cycle energy impacts. Assessment of broader-scale environmental impacts, as well as opportunities to reduce those impacts, are relevant for all components of the life cycle. *One of the major research needs identified was the development of accepted methodologies to conduct the Impact Analysis and Improvement Analysis.*

This chapter briefly discusses the link among the inventory and the impact and improvement analyses components of a life-cycle assessment. First, an inventory-based approach to “previewing” environmental impacts is presented. Then general considerations regarding the scope and content of the impacts and improvement analyses are discussed. Clearly, these components of a life-cycle assessment will require methodology and concept development. These two components are an extension of the traditional view of life-cycle assessments, which originally included primarily the inventory component. As such, considerable research is needed to develop the concepts and methods: *Another major area for initial research is the establishment of approaches to bridge the gap between the inventory and assessment components.*
10.1 THE BRIDGE FROM INVENTORY TO ANALYSIS

It has already been acknowledged that an inventory does not attempt to directly assess the potential environmental effects associated with its inputs and outputs. However, in many cases, cataloging the available qualitative or semiqualitative data on environmental loading can provide useful information and facilitate the transition to an actual analysis of impacts. Similarly, such an exercise may suggest measures for emission reduction that could be instituted in the short term.

A broad range of possible effect categories could be included at this stage. The following is a brief description of factors that should be considered wherever possible and appropriate:

- **Ecological Effects**—Ecological effects specific to a process and/or region of the manufacturing site should be listed in the inventory phase. Where available, the inventory should reference or include quantitative information from an environmental impact study.

- **Site Selection**—When new manufacturing facilities are to be constructed and alternative decisions are possible, special consideration can be given to all interfaces with human and environmental resources; i.e., population centers, schools and hospitals, roads, and uniquely valued ecosystems. During an inventory component any quantitative information available could be used.

- **Habitat Alteration**—For new construction and expansion of manufacturing facilities, consideration should be given to how many acres of land will be removed from an ecosystem and the intrinsic value of the resources that will be destroyed. Routine emissions and discharges or spills could also contribute to habitat alteration. The value of these resources can be examined further in the assessment phase.

- **Good Management Practices**—Good management practices (GMP), whether voluntary or required, have impacts that may be useful for consideration whether or not they are quantifiable.

- **Manufacturing and Use of Manufacturing Products**—A life-cycle assessment for a manufacturing process should, in some instances, include a review of the environmental impacts (loadings) resulting from manufacturing the equipment used in a plant.

- **Worker Health Concerns**—Worker health and safety concerns such as noise, chemical exposures, and accidents should be considered (i.e., adherence to all relevant OSHA regulations).
In addition, the following two areas are important to consider in any life-cycle assessment:

- **Community Relations**—A manufacturing site should have a cooperative working relationship with the community so that there is a partnership of concern and action for an overall improvement in the environmental quality of life.

- **Public Perceptions**—Even when data do not exist on environmental and human health issues, it is prudent to consider public perception in these areas.

Including these considerations may cause difficulties because they are often site specific; they are difficult to quantify compared with many of the common energy, material, and waste types of inputs and outputs. Attempting to include them poses new challenges in interpreting the results. Nevertheless, these considerations should be examined through general discussions and reliance upon other documents, quantified to the best extent possible, and incorporated into the inventory with the aim of preparing a more comprehensive database. It is expected that as the life-cycle assessment methodology evolves, these areas of potential impact will also further develop with respect to quantification and increased utility.

### 10.2 GENERAL CONSIDERATIONS FOR THE LIFE-CYCLE IMPACT ANALYSIS COMPONENT

The impact analysis organizes information on the environmental consequences of the quantitative loadings defined in the inventory as well as such less quantifiable effects as noise or aesthetic changes. A variety of impact assessment methods may be appropriately applied depending on the geographic scale, type and duration of the effect, and the level of interpretive accuracy desired. These methods range from a straightforward interpretation of the significance of a loading to site-specific risk assessments requiring significant additional data beyond that normally developed in the inventory. Guidelines for the selection of an optimal method or methods have yet to be developed because the impact assessment component of a life-cycle assessment is less well developed than the inventory component.

#### 10.2.1 Direct Use of Inventory Data

In some instances it should be possible to recognize and interpret directly the consequences of an environmental loading. Examples include comparison of the quantities of process and post-consumer solid waste from a product versus annual per capita rates and comparison of energy use versus annual per capita rates (i.e., the lower the better). Either of these measures might also be converted into economic impacts by using current cost factors.

#### 10.2.2 Hazard Assessment

Where environmental loadings consist of materials with associated toxicity and/or bioaccumulation potential, these intrinsic properties can be used along with the loading quantities and measures of persistence and environmental mobility to score the potential relative effects of the releases. Ranges of the environmental parameter and the quantity can be combined to derive a hazard-potential index. These index values may be used themselves as measures of potential effects or may be used as a screening parameter to determine the need for and scope of a more extensive risk assessment.
10.2.3 Risk Assessment Impacts

Risk assessment may be a component of the life-cycle impact analysis where there is an indication that a specific category of environmental burdens are of potential concern, but it is not the sole component. A risk assessment uses the total loading data from the inventory augmented by more site-specific data to characterize the potential of environmental emissions to affect human or environmental health. Environmental loading information must be subjected to fate-and-transport analysis to determine how the releases will be transferred to various environmental compartments (air, water, and soil). The exposure pathways by which humans or other organisms will be exposed to the pollutants must be delineated, and the amount of each pollutant that is taken up must be quantified. Finally, toxicological data are used to determine the health endpoint. Most often the performance of a risk assessment will necessitate the collection of environmental data in air, water, and soils as well as in the living parts of the system.

Risk assessment can be carried out for both specific and generic processes, facilities, products, and so forth. For a generic assessment, a hypothetical population is often used, setting up “typical” or “reasonable worst-case” conditions such as the amount of fish from a nearby stream that people eat and the amount of locally grown vegetables consumed. The assessment is carried out as specified above.

It must be stressed that risk assessment is only one tool in the impact analysis component. Risk assessment does not generally assess environmental impacts such as ozone depletion, greenhouse gas impacts, habitat loss, soil loss, or critical resource depletion. Other assessment techniques should be employed to characterize these impacts.

10.2.4 Nature of Health Risks and Environmental Effects that May Be Considered

The life-cycle impact analysis of processes or products should be completed and assessed with respect to a broad range of health and environmental effects. Effects not specifically linked to individual pollutants should be included. Following is a preliminary list of the nature of health and environmental impacts that deserve consideration:

- **To Air**—Toxic, carcinogenic, teratogenic, mutagenic, corrosive, ozone depletion, greenhouse precursor, weather alterations, visibility alterations, fog inducing, smog precursor, dust producing, odorous, habitat alteration, radioactive, allergenic, persistence, bioaccumulative, noise, irritating to eyes and mucous membranes

- **To Water**—Toxic, carcinogenic, teratogenic, mutagenic, corrosive, thermal effluent, turbidity producing, color alteration, oxygen depletion, turbulence producing, eutrophication enhancing, habitat alteration, radioactive, allergenic, persistence, bioaccumulative, taste alteration, pH alteration, litter, aquifer depletion, altering of chemical and biological content

- **To Solid Waste**—Toxic, flammable, corrosive, explosive, habitat alteration, persistence, bioaccumulative, carcinogenic, teratogenic, mutagenic, odorous, pH alteration, litter
10.3 GENERAL CONSIDERATIONS FOR THE IMPROVEMENT ANALYSIS COMPONENT

The third component of a life-cycle assessment is a systematic evaluation of opportunities for reducing impacts of a product, process, or activity on the environment. This component requires extensive development work with respect to scope, methodology, and expected or desired outputs. The discussion here is therefore by necessity sketchy and preliminary in nature.

Opportunities for impact reduction include:

• Minimization of energy and raw material consumption

• Closed-loop systems for chemicals that are bioaccumulative, persistent, etc.

• Minimization of activities resulting in species endangerment through habitat destruction

• Minimization of waste releases.

Some ways of achieving these goals include:

• Maintaining ownership of products containing toxic substances or high inherent value

• Requiring implementation of good manufacturing practices

• Improving energy and materials efficiency

• Improving recycling systems to make better use of waste products.

For example, keeping ownership of products that contain hazardous substances can prevent their release to the environment. This system can be applied to products that contain rare chemicals (i.e., bismuth), hazardous substances, and high energy consuming materials (i.e., aluminum) to ensure that these resources are recovered (i.e., by requiring products to be returned to the producers). Examples of this type of system now in effect include a solvent renting program at a U.S. chemical company and a junk car disassembly program by a European car manufacturer.

Good manufacturing practices are required in the manufacture of certain products, especially foods, drugs, cosmetics, and medical devices, to ensure their integrity. In such processes, one must consider that chemical or process changes which might show an overall optimization may result in an end-product that would be in violation of regulatory statutes and therefore unacceptable.
In addition to environmental benefits, an impact improvement analysis could yield results that benefit producers by reducing raw materials, energy, and waste-treatment costs.

10.4 ENVIRONMENTAL RISK ASSESSMENT VERSUS ENVIRONMENTAL ANALYSIS

An environmental risk assessment requires a site-specific and detailed chemical, physical, and biological understanding of a chemical of interest (e.g., specific emission component). Such information would translate into an understanding of both the inherent toxicity of the material as well as the environmental exposure. Both parts of this “equation” are necessary to fully assess the potential of an emission to the environment to cause an environmental effect. Such detailed information is generally not available for many of the environmental releases quantified in the life-cycle inventory. Therefore, direct extrapolation from the inventory to application in a risk assessment context is not possible without additional information.

On the other hand, many environmental releases (NPDES-regulated releases, priority pollutants, etc.) have already been evaluated from a risk assessment context. That is, emissions are controlled to minimize the release of potentially harmful substances and such substances are released at concentrations below concentrations that could cause environmental effects. Recognizing that some materials in “complex effluents” or other process emissions may escape detection, current discharge regulations also require that environmental discharges be nontoxic to all relevant environmental compartments that receive them.

In the absence of additional information, one assumes that a legal discharge is an environmentally safe discharge. However, given the uncertainties inherent in such assumptions, it is prudent to minimize waste emissions wherever they occur and develop alternative processes and materials that result in lower overall emissions to the environment. Clearly on a “kilogram-per-kilogram” basis, one would opt to replace a relatively toxic or persistent emission component with a more biodegradable and less toxic alternative.

The life-cycle inventory may be a useful tool to identify, not only opportunities for overall environmental improvement, but also data gaps where more information may be required to better understand the physical, biological, and chemical behavior of a given compound or suite of compounds in a site-specific context. In some cases, this might require a risk assessment-based analysis, although such a comprehensive assessment for all chemical-specific components of all possible environmental emissions at all locations is not feasible or necessary to ensure the environmental safety of a given process or product.
GLOSSARY

actual life: See useful life.

ancillary material: A material that is used by the manufacturing system producing that product, but is not used directly in the formation of the product.

byproduct: Material, other than the principal product, that is generated and retained for further commercial purposes because it has some alternative value or function.

closed-loop recycling: Reclaiming, re-using, or reprocessing waste product into a similar product.

coproduction: See byproduct.

distribution: All nontransportation activities carried out to facilitate the transfer of manufactured products from their final manufacturer to their ultimate end user. This includes the movement of goods within a warehouse or retailing establishment.

end user: Entities (individual consumers, commercial businesses, institutions) that actually use (unpack and consume, operate, store for their later use, or prepare for their use) a finished product.

finished product: A product in the form in which it will be used, including any primary packaging.

formulating: Processing or making a product by mixing or combining materials in an operation that does not involve the synthesis of a new chemical substance.

fugitive emissions: Emissions that escape control devices.

HAPS: Hazardous Air Pollution Standards.

insert: A component that is both an input and output to a process, and is not transformed or otherwise acted upon.

landfill: (a) Sanitary landfills are land disposal sites for nonhazardous solid wastes at which the waste is spread in layers, compacted to the smallest practical volume, and cover material applied at the end of each operating day. (b) Secure chemical landfills are disposal sites for hazardous waste. They are selected and designed to minimize the chance of release of hazardous substances into the environment.¹
maintenance: Includes activities such as on-site (e.g., home) repair (which may require a trip to the hardware store for parts), off-site repair by a repair service, preventive maintenance (e.g., changing the oil in a car, washing laundry). On-site maintenance may require trips away from the site to obtain supplies and then back to complete the maintenance activity. Off-site maintenance includes transport to and from the site of the maintenance facility. Maintenance may occur at the site of the end user or at another site.

manufacturing: A process or series of processes using one or more materials to make a product.

manufacturing, process, and formulation: The portion of a life cycle that converts feedstocks or raw materials into final products.

mass balance: Mathematical expression in which a summation of all material inputs to a system is equated to a summation of all outputs, accounting for transformation into energy.

NAAQS: National Ambient Air Quality Standards.

nonenergy raw materials: Minerals, agricultural and forest products, water, and so forth.

open-loop recycling: Reclaiming, re-using, or reprocessing waste product into a different product.

post-consumer recycled materials: Any material generated by consumer, business, or institutional sources that has served its intended end use and has been separated from municipal solid waste for the purpose of recycling.²

precombustion energy: An energy figure adjusted to account for the energy required to extract the raw material.

pre-consumer recycled materials: Pre-consumer recycled materials are materials and byproducts that have not reached a consumer for an intended end use and have been recovered or diverted from solid waste, but are not those re-used within an original manufacturing process.²

primary energy raw materials: Natural gas, petroleum, coal, nuclear, hydro, and so forth.

process: An operation performed on one or more raw materials or intermediates leading toward the formation of a product.

processing: See manufacturing, processing, and formulation.

product: Something produced that has an existing value or potential use.

raw material: A primary or secondary (e.g., recovered and/or recycled) feedstock that is used in a subsequent manufacturing process.

recyclability: Defined by reference to an actual recycling rate as measured in the area set by the study scope (e.g., state, region, nation).²
SARA: Superfund Amendment and Reauthorization Act.

recycled content: The portion of a product or package that is composed of recycled materials, measured by weight.\(^2\)

recycled material: Material that would otherwise be destined for disposal as solid waste, but is refabricated into marketed end products. This includes, but is not limited to, post-consumer material, industrial scrap material, and overstock or obsolete inventories from distributors, wholesalers, and other companies. It does not include those materials and byproducts generated from and commonly re-used within an original manufacturing process.\(^2\)

recycling: The life-cycle activity that diverts materials from the waste management system and delivers them to the manufacturing and processing sector.

renewable resource: A resource that is being replenished at a rate equal to or greater than its rate of depletion.

re-use: Includes both on-site (e.g., home) and off-site re-use. On-site re-use may include intentional re-use of a product or package for its original purpose (e.g., Tupperware\(^\circ\)) or incidental re-use for a different purpose (e.g., storage of paint brushes in an old mayonnaise jar). Off-site re-use may include the return of materials to a retailer or manufacturer to be re-used for their original purpose (e.g., a refillable beverage bottle), donating of used items to charities for re-use by another party; off-site re-use also includes rental equipment.

secondary data: Published or unpublished data reflecting the results of previous data collection and analyses.

secondary raw material: A recovered and/or recycled raw material.

semiproduced material: The product of a preliminary processing stage that requires further processing.

transportation: Movement of materials or energy between operations at different locations.

use: Activities such as consumption of a product, operation of equipment, storage of a product for later use (e.g., refrigeration), or preparation of a product for use (e.g., cooking).

use/re-use/maintenance: The life-cycle activities that begin after the distribution of products or materials and end when those products or materials are discarded and enter a waste management system.

useful life: The period of time from when the product arrives in the hands of the end user at the point of use to when that product has been used by the end user and is discarded. It can be expressed in any of a number of units that reflect the actual use patterns of the product.
waste: (a) An output with no marketable value that is disposed to the environment. (b) Any material released to the environment through either air, water, and/or land, and has no beneficial use.

waste management system: The mechanism for treating or handling a waste prior to its release to the environment.


2. Source: These definitions are based upon the working definitions from a joint Task Force of the Coalition of North East Governors Source Reduction Council and North East Recycling Council.
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