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EPA/600/R-01/101
November 2001

Life Cycle Engineering Guidelines

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Foreword

This publication has been produced as part of the Strategic Environmental Research and Development Program (SERDP) strategic long-term research plan. SERDP was established in order to sponsor cooperative research, development, and demonstration activities for environmental risk reduction. Funded with U.S. Department of Defense (DoD) resources, SERDP is an interagency initiative involving the DoD, the U.S. Department of Energy, and the U.S. Environmental Protection Agency (EPA). SERDP seeks to develop environmental solutions that improve mission readiness for Federal activities. The Life-Cycle Engineering and Design Program (LCED) is a product of the SERDP effort coordinated by the EPA to provide a technical and economic basis for the effective application of life cycle principles to product and process design and materials selection. In addition, it is expected that many techniques developed will have applications across both the public and private sectors.

This document has been published and is made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients. This document is preceded and is partially based on previous reports in this series where the application of life-cycle assessment (LCA) and total cost assessment (TCA) methodologies to research and demonstration projects under support from the SERDP are summarized and several lessons learned are documented.

Contents

1. Introduction

To meet the needs of today's market place, product, process, and facility engineering is a concurrent effort involving engineers, business planners, marketing staff, and environmental professionals who function as integrated teams. Consideration of cost and mechanical, electrical, and chemical performance requirements has long been a part of product, system, process, and facility engineering decisions. However, integration of a broader set of factors into these decisions, such as environmental implications, is a fairly recent phenomenon.

This guide was prepared under the cooperating programs of both the Department of Defense (DoD) and the Environmental Protection Agency (EPA). Among the shared objectives of the cooperators is demonstrating the effectiveness of analytical tools and environmental techniques to reduce environmental impacts and costs of operations while maintaining performance standards. This project was sponsored by the DoD's Strategic Environmental Research and Development Program (SERDP) and conducted by the EPA's Life Cycle Assessment Research Team at the National Risk Management Research Laboratory. It builds upon prior research sponsored under the Program and conducted by EPA.

Improving Mission Readiness Through Environmental Research

SERDP was established in order to sponsor cooperative research development and demonstration activities for environmental risk reduction. Funded with DoD resources, SERDP is an interagency initiative among DoD, the Department of Energy (DOE), and EPA. SERDP seeks to develop environmental solutions that improve mission readiness for Federal activities. In addition, it is expected that many of the techniques developed will have application across the public and private sectors.

Within the context of this engineering guide, environmental implications are beneficial or adverse effects on human health and the environment with respect to material and energy use and waste in the context of industrial operations. Environmental implications occur throughout the stages of the product, process, or facility life cycle—that is, from the acquisition and processing of materials, through production or construction, use, maintenance, and retirement. A reliable and comprehensive characterization of a product, system, process, or facility reflects environmental implications throughout the life cycle stages in conjunction with cost and mechanical, electrical, or chemical performance requirements.

Life Cycle Engineering (LCE) uses such a characterization in product, system, process, and facility engineering decisions. The LCE process is an ongoing, comprehensive examination with the goal of minimizing adverse environmental implications throughout the life cycle. LCE provides a means to:

- communicate the relationship between environmental implications and engineering requirements and specifications,

- assess the environmental implications of alternatives, and
- identify improvement opportunities throughout the life cycle.

LCE depends on understanding performance, cost, and environmental implications and translating them into engineering requirements, goals, and specifications. Related decisions are iterative in nature. As the engineering process proceeds from the conceptual to defined, the LCE evaluation will reevaluate earlier decisions and expand or contract the coverage to ensure that the broadest set of improvement opportunities are considered, substantial environmental implications are not missed, and consequences are not inadvertently shifted from one life cycle stage to another. Through repeated application, engineers, managers, and other technical experts become progressively more proficient in using LCE.

The purpose of this document is to provide guidelines for the implementation of LCE concepts, information, and techniques in engineering products, systems, processes, and facilities. To make this document as practical and useable as possible, a unifying LCE framework is presented. Subsequent topics are organized according to a classification scheme that reflects the generic types of engineering decisions that are candidate to include environmental implications in conjunction with cost and performance requirements. This organization is summarized and shown in Table 1.1.

Table 1.1 LCE Decisions

		Product	System	Process	Facility
New	Original	Section 3.1		Section 3.2	
	Improvement				
Upgrade		Section 4.1		Section 4.2	
Maintenance	Routine		Section 5.1	Section 5.2	
	Unanticipated				
Decommissioning			Section 6.1	Section 6.2	

1.1 What Is Life Cycle Engineering?

Life Cycle Engineering (LCE) is a process to develop specifications to meet a set of performance, cost, and environmental requirements and goals that span the product, system, process, or facility life cycle. The life cycle embodies material and energy use and waste throughout four conceptual stages:

Stage 1. **Material Production.** Material production includes material acquisition and processing. Material acquisition includes activities related to the acquisition of natural resources. This includes mining non-renewable material and harvesting biomass. Material processing involves processing of natural resources by reaction, separation, purification, and alteration steps in preparation for the manufacturing stage.

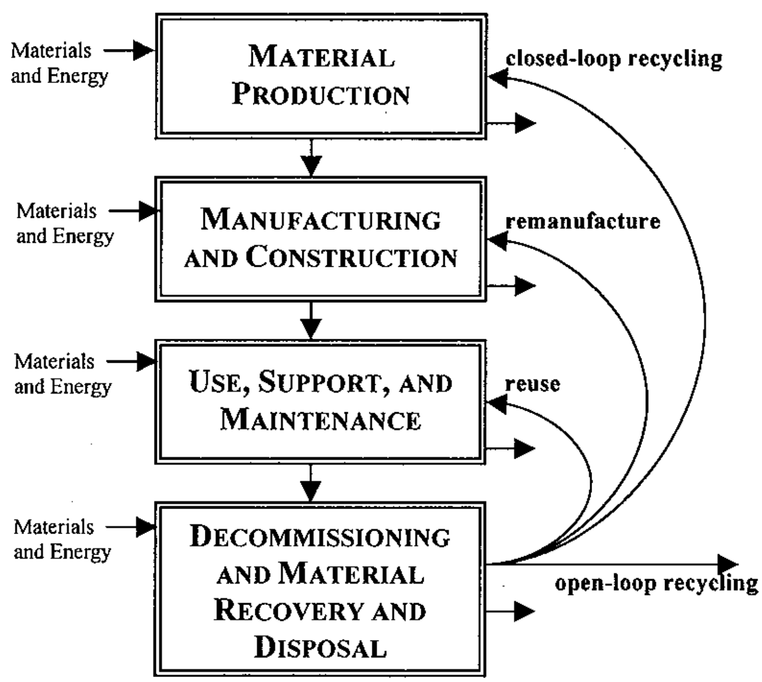
Stage 2. **Manufacturing and Construction**. Manufacturing and construction involves the creation of parts and their assembly into the products.

Stage 3. **Use, Support and Maintenance**. Products, systems, processes, and facilities are used, maintained, and repaired.

Stage 4. **Decommissioning and Material Recovery and Disposal**. Retirement and disposal of products, systems, processes, and facilities includes the decommissioning, disassembly, the recovery of usable components, materials and energy, and the treatment and disposal of residual materials.

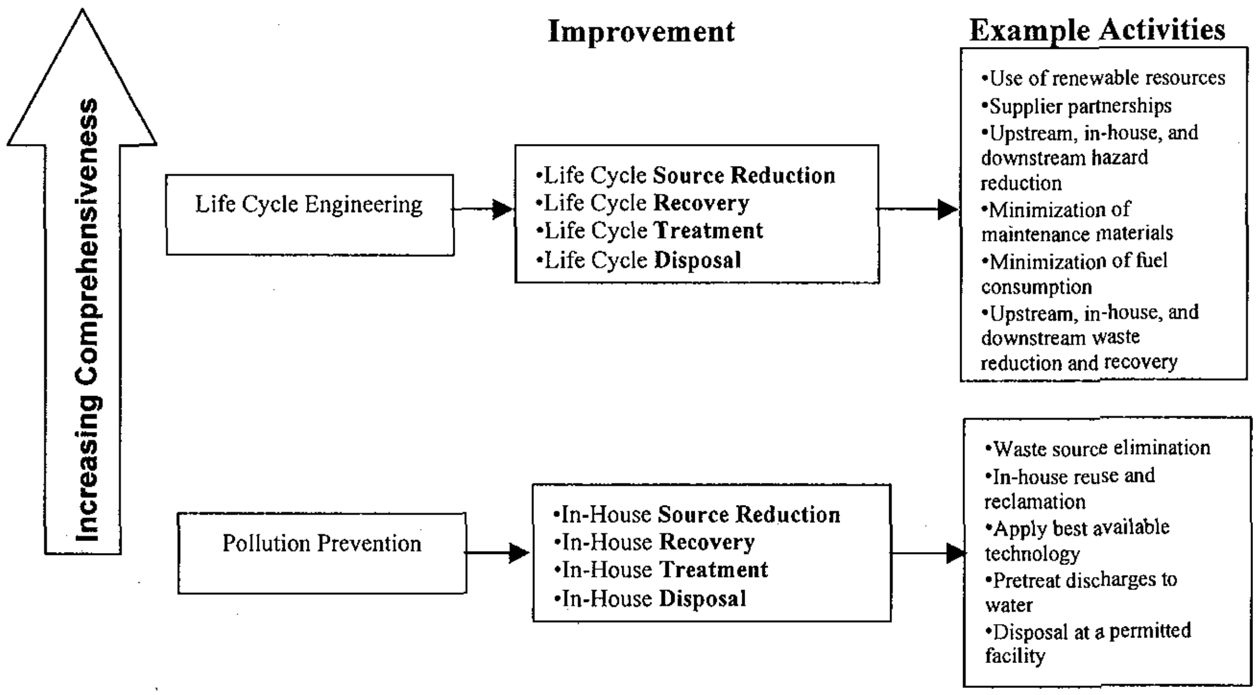
Figure 1.1 portrays these four life cycle stages. Materials and energy flow into and between each life cycle stage, are recovered, and wasted. Recovery includes the reuse of components and materials, the remanufacture of components, and the recycling of components and materials. Recycling includes both closed-loop, in which materials are reused within the same product life cycle, and open-loop, in which materials are used in other products and processes.

Figure 1.1 Life Cycle Stages



Like pollution prevention, LCE can be considered as the judicious use of resources through source reduction, energy efficiency, and material recovery. Unlike pollution prevention, LCE considers environmental implications beyond facility gates, or beyond what applies "in-house," such that environmental implications are not transferred to another facility within the life cycle. Thus, as illustrated in Figure 1.2, LCE offers a platform to apply improvement strategies and identify engineering activities in a manner more comprehensive than pollution prevention with respect to the life cycle.

Figure 1.2 Life Cycle Engineering and Pollution Prevention

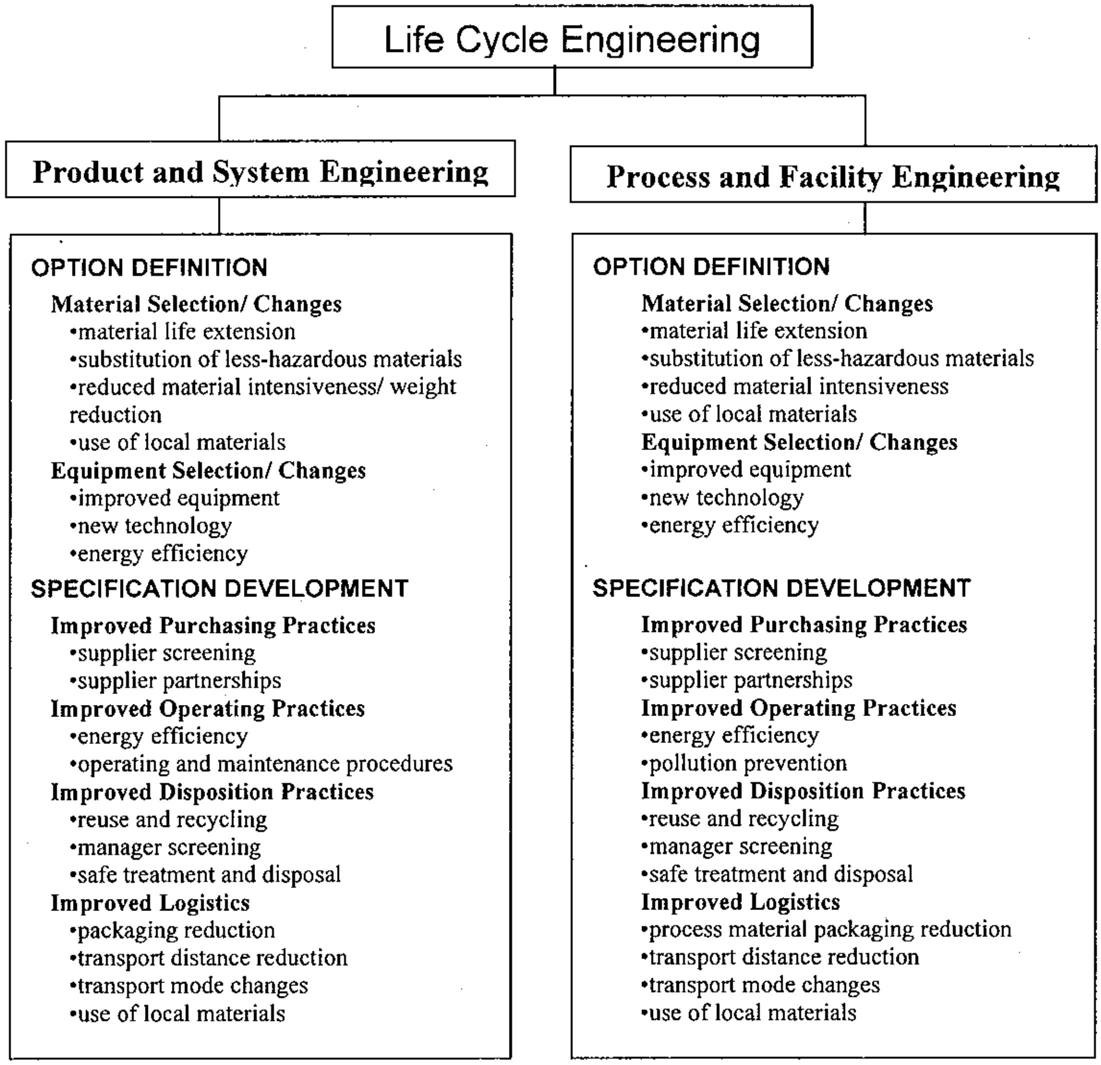


There are six categories of engineering activities that can be used in LCE as applied to product and system engineering and process and facilities engineering:

1. material selection/ changes,
2. equipment selection/ changes
3. improved purchasing choices,
4. improved operating practices,
5. disposition practices, and
6. improved logistics.

Material and equipment selection/ changes produce improvements through the definition of resource flows and operations within the life cycle. The latter four categories, improved purchasing, operating, and disposition practices, and improved logistics, are dictated within LCE by carefully crafted engineering specifications as a complement to material and technology changes. These categories and example activities are listed in Figure 1.3.

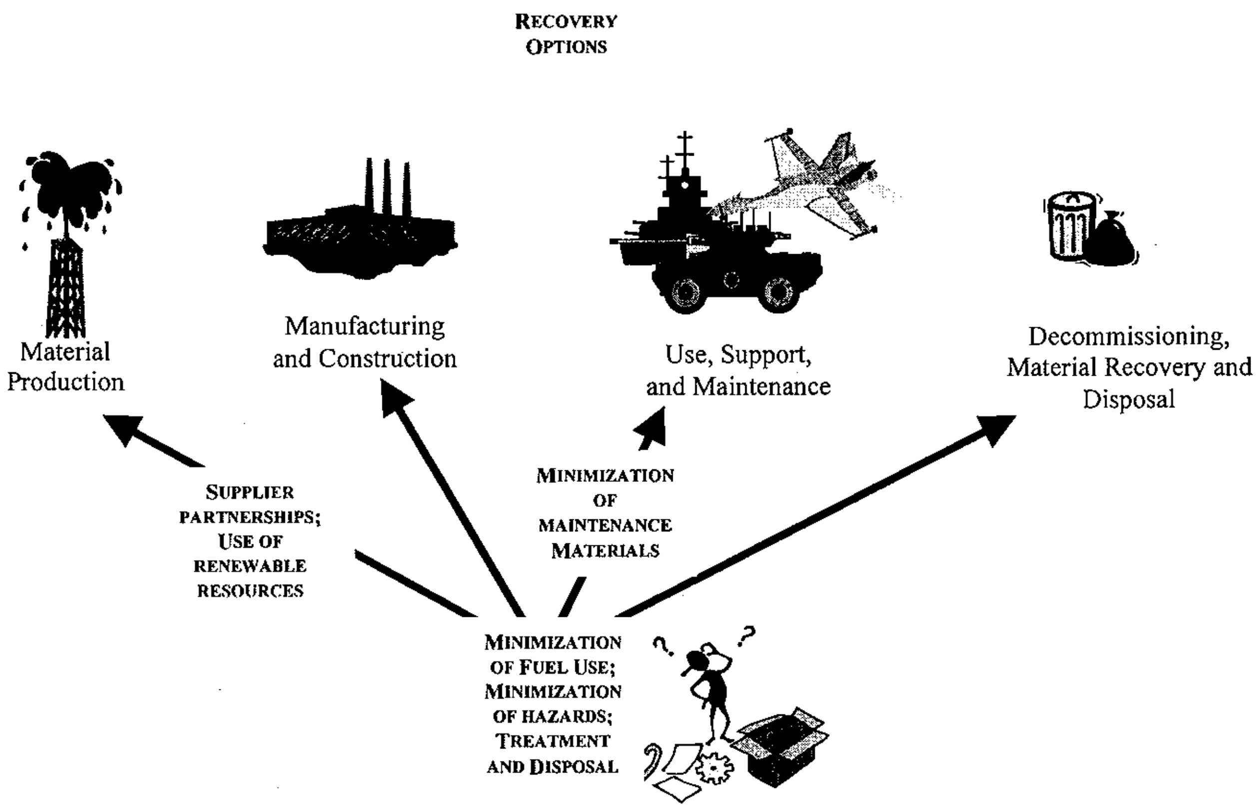
Figure 1.3 Life Cycle Engineering Activity Categories



Considering environmental implications beyond what applies in-house is a concept that promises to help engineers expand the scope of requirements and specifications. As illustrated in Figure 1.4, identifying and choosing specific activities can be a daunting task. LCE seeks to provide a systematic framework to identify and select among activities given a life cycle perspective.

LCE provides a comprehensive evaluation of how engineering decisions and specifications affect not only your company but also your suppliers, customers, and waste managers throughout the associated life cycle. Therefore, LCE is often broader in scope when compared to engineering decisions you currently make.

Figure 1.4 Which Activity is Best from a Life Cycle Perspective?



1.2 Benefits of Life Cycle Engineering

Life Cycle Engineering provides benefits in a number of areas. These include tangible benefits in the form of reduced environmental burdens at the location where the primary activity takes place. However, by understanding the whole life cycle, the engineering team can often identify and realize additional benefits upstream in the supply chain and downstream in customer organizations or during end-of-life management. Many times these situations are positive both within the decision-making organization and outside of it.

Many practitioners of LCE find that environmental impact reduction and cost savings are not mutually exclusive. Even when the benefits occur in supplier or customer organizations, it is possible to negotiate shared savings in the form of price reductions for raw materials or waste handling, as an example. The key to providing incentives for the LCE team is finding ways to recognize and reward their efforts to realize the benefits of LCE regardless of where they occur. In order to do this, it may be necessary to catalog the external benefits using measures other than monetary indicators.

1.3 Institutional Barriers

As with any other new program, general resistance to change within your company may arise. These can result from many factors, such as lack of awareness of corporate goals and objectives, individual or organizational resistance to change, lack of commitment, poor internal communication, or an inflexible organizational structure.

Analyze these barriers from different perspectives in order to understand the concerns. Engineers are concerned with chemical, mechanical, and thermal performance; production, support, and maintenance costs; process efficiency; and in-house environmental management. They are typically not concerned with how these things are managed by up and downstream companies. Educational and outreach programs can overcome such institutional obstacles.

2. A Life Cycle Engineering Framework

The Life Cycle Engineering Framework (LCEF), presented in Figure 2.1, is intended to provide a systematic means of considering life cycle environmental implications during engineering decision-making. The steps shown are described in the sections of this chapter. Subsequent chapters describe and illustrate the application of the framework to specific engineering decisions: new designs, upgrades, maintenance, and decommissioning. Worksheets, provided in the Attachments, are used to facilitate assessments within the LCEF.

The first two steps in the LCEF, *Option Definition,* relate to technology selection and changes and support the development of the technical order. During these steps, the function being provided is identified, an evaluation team is formed, requirements and goals are established, and preliminary assessments apply a graded approach to identify a set of preferred engineering options. It is at this time that key decisions concerning the use of materials and equipment are made.

The latter two steps in the LCEF, *Specification Development,* relate to specification development and support the development of the process order. It is during these steps that more detailed information about the life cycle is used to *refine* preferred engineering options. Areas for improvement are addressed to the extent possible.

2.1 Targeting the Assessment

2.1.1 Establishing the Function being Provided

Perhaps the most important aspect of LCE is the characterization of the function being provided. The function is a conceptual formulation of an engineering task, independent of a specific solution. Truly understanding the function being provided,

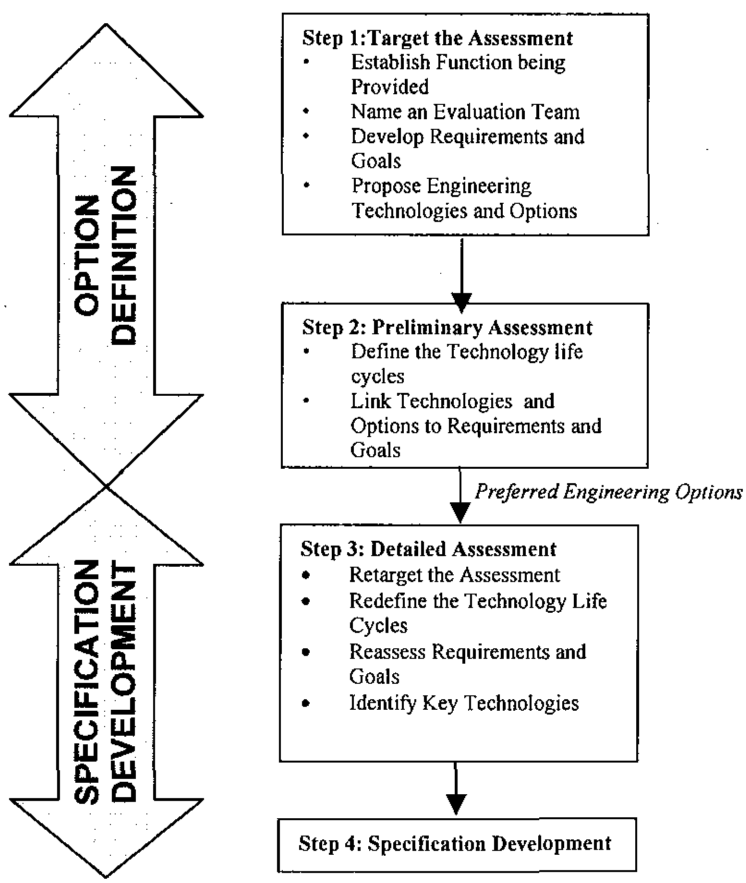
- allows the evaluation to determine if an engineering solution meets the identified need,
- enables the most comprehensive set of improvement activities being identified, and

- allows options being compared on a standard basis, called the *functional unit.*

One approach to establishing the function being provided is to answer a series of simple what and why questions. For example:

- What needs to be accomplished?
- Why does it need to be done?
- When does it need to be done?
- What conditions must be considered?

Figure 2.1 Life Cycle Engineering Process



As an example, suppose the evaluation are asked to paint a particular part. To understand the function being provided, the team might ask, "what is being enhanced or enabled by painting this part?" Responses could range from improving aesthetics to protecting the part from wear or corrosion. Understanding what conditions the part must withstand helps in the identification of important engineering team members and the development of requirements and goals.

2.1.2 Naming an Evaluation Team

People who will participate in the LCE process should be selected carefully. They have the responsibility for developing and collecting information for LCE assessments. Their capabilities and attitudes towards the effort will determine how successful the effort will be.

First, the evaluation team should be representative of **engineering development**—that is, the team should include anyone who will be involved in the development of an engineering solution to the function being provided. This would include engineers involved in the development or application of materials, equipment, or facilities. Second, the team should be representative of the **life cycle**—that is, the team should include representatives with responsibility for or an understanding of:

- *material production* (e.g., someone from purchasing and materials engineering);
- *manufacturing or construction* (e.g., someone from materials management, manufacturing or construction operations, and waste management); and
- *use, support, maintenance and decommissioning* (e.g., someone from marketing, program management, or others representing the customers present and future needs).

Evaluation team members will have varying levels of participation in the LCE effort. The full team should be engaged in goal setting, brainstorming, and review activities. It may, however, be practical to leave information collection, management, and assessment to a subset of the team.

2.1.3 Developing Requirements and Goals

The evaluation team needs to (1) **understand** mechanical, physical, and chemical performance and cost requirements and goals and (2) **develop** environmental requirements and goals. Requirements can be thought of as things the team *must have*, and goals can be thought of as things that would be *nice to have*. Well-defined requirements and goals will focus the identification of engineering options as well as information collection and assessment throughout the LCE process. Requirement and goal-setting activities should involve all team members and incorporate the needs and concerns of all members.

Environmental requirements and goals should be consistent with company policies and customer program needs and concerns. The evaluation may even choose to engage environmental groups, local throughout the life cycle or groups with broader interests, or other stakeholders. One way to develop environmental requirements and goals is to identify categories of environmental policies, needs, and concerns and then develop specific requirements and goals within each category. Table 2.1 lists example categories of environmental concerns as linked to qualitative requirements and goals. Quantitative requirements and goals use metrics to measure the attainment of goals either in absolute terms or relative terms as an improvement from a baseline.

The first worksheet in each of the attachments, *Developing Requirements and Goals*, provides a template to facilitate the identification of performance, cost, and environmental requirements and goals within an example set of environmental policy, needs, and concern categories. The worksheet also allows for the identification of the life cycle stage to which the requirement or goal applies and the identification of technology designations. This should help the evaluation identify goals with a larger scope: considering the full life cycle of performance, cost, and environmental implications.

Table 2.1 Example Environmental Requirements or Goals

Categories	Example Environmental Requirements or Goals
Facility	
Use and waste of regulated materials	Reduce or eliminate the use and waste of toxic materials throughout the life cycle. Reduce or eliminate the use and waste of flammable and explosive materials throughout the life cycle. Reduce or eliminate the need to store and discharge hazardous materials throughout the life cycle. Meet or exceed all regulatory requirements.
Energy consumption	Reduce the consumption of energy throughout the life cycle.
Local	
Contribution to photochemical smog	Reduce or eliminate the use and waste of chemicals linked to smog formation throughout the life cycle.
Contribution to water pollution	Reduce or eliminate discharge to surface water and disposal potentially linked to water pollution throughout the life cycle.
Contribution to toxic materials in the environment	Reduce or eliminate the use and waste of process toxics throughout the life cycle. Reduce or eliminate toxic emissions from products and systems.
Contribution to landfill space	Reduce or eliminate solid waste generation throughout the life cycle.
Contribution to oil spills	Reduce the use of oil throughout the life cycle.
Regional	
Contribution to surface water chemistry changes	Reduce or eliminate the purchase of materials from processes or facilities with acidic or alkaline water discharges throughout the life cycle.
Contribution to soil degradation	Minimize or eliminate activities that disperse heavy metals or persistent, bioaccumulative toxic materials into the atmosphere. Minimize soil disturbance and overuse.
Contribution to precipitation acidity	Minimize or eliminate activities, such as fuel combustion, that disperse oxides of sulfur and nitrogen.
Contribution to visibility problems	Improve logistics (products, systems, and packaging) to minimize transportation requirements throughout the life cycle.
Global	
Contribution to climate change	Reduce or eliminate the use of chemicals linked to global warming and ozone depletion throughout the life cycle. Reduce or eliminate the contribution to climate change throughout the life cycle.
Contribution to loss of habitat and reductions in biodiversity	Do not create a need for new industrial facilities anywhere in the life cycle. Reduce or eliminate the use of materials from virgin forests and protected regions throughout the life cycle.
Conservation of resources	Maximize the use of recovered materials and energy throughout the life cycle. Maximize recovery of components and materials throughout the life cycle. Reduce or eliminate from use scarce materials throughout the life cycle. Maximize the use of non-fossil fuel energy sources throughout the life cycle.

2.1.4 Proposing Engineering Technologies and Options

Once the evaluation team has identified `requirements and goals,` the team should identify *technologies* that combine to form different *options* to provide the desired function. Within this context, technologies include materials and equipment that together provide a solutions including how the function has been provided in the past. Changes from this baseline result from the addition of performance, cost, and environmental requirements and goals. Thus, these additional requirements and goals can be used to identify additional technologies and options and areas for innovation.

Traditional techniques for identifying engineering technologies and options include brainstorming, cause/effect diagrams, and benchmarking the best practices and technologies of the public and private industrial sectors. A useful technique to incorporate these activities into the LCE process is to identify desirable types of materials and equipment based on the improvement strategies presented in Figure 1.2. Table 2.2 provides example technology types as linked to improvement strategies.

Table 2.2 Identifying Desired Technologies

		LCE Improvement Strategy		
Technology Category	**Desired Technology Types**	**Source Reduction**	**Recovery**	**Treatable**
Materials	non regulated/ contributory[1]	x		
	non-energy intensive	x		
	non-water intensive	x		
	recoverable		x	
	treatable as waste			x
Equipment	material efficient	x		
	energy efficient	x		
	material recovery		x	
	energy recovery		x	
	treatable wastes			x

Desired and other technologies combine into options that together provide the function. Different technologies may be used in different amounts to achieve the same functional unit. For example, if the functional unit is person-miles traveled, the amount of fuel required to power by motorcycle is different than that of an automobile.

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[1] For example, not contributing to global warming, smog formation, etc.

In addition to understanding the quantitative mix of technologies, how materials and equipment are combined is called the *configuration status* as shown in Table 2.3. The configuration status is intended to help the team understand how complicated it will be to:

- **recover** components and materials and
- **maintain and upgrade** products and equipment.

Table 2.3 Technology Configuration Status

Configuration Status	Abbreviation	Technology Category	Description
simplified	SIMP	materials	The number of different materials and components have been minimized.
		equipment	The number of production or maintenance steps have been minimized.
accessible	ACC	materials	Recoverable materials can be accessed during maintenance and during decommissioning.
		equipment	Equipment use, support, and maintenance is facilitated by accessibility of equipment parts.
modular	MOD	equipment	Equipment is made up of parts that can be upgraded or replaced when warn or damaged.
joining status	JS	materials	Incompatible materials are not permanently joined (welded or otherwise physically or chemically adhered).

Worksheet 2 in each of the attachments, *Proposing Technologies and Options* provides a template to identify material and equipment technologies and to quantify the relationship between technologies and the functional unit. Evaluation team participation is crucial for success. Identifying associated desirable technology types and configuration statuses should facilitate innovation among team members.

2.2 Preliminary Assessment

2.2.1 Defining the Technology Life Cycles

Defining the life cycle is very similar to defining processes within a process flow diagram. Using the stages of the life cycle as a guide, individual processes are linked by the flow of materials and energy. The diagram should be extended far enough upstream to capture material production and far enough downstream to capture decommissioning. The cycle is created when recovery opportunities, either within the life cycle or within other life cycles are realized. The total life cycle should provide a single functional unit or a quantity of functional units equal to anticipated use or production levels.

In the preliminary assessment, defining the technology life cycles is intended to help the evaluation better understand the environmental implications of in-house, up- and down-stream processes. In-house processes are within the direct influence of the team. This includes operations within your organization or within organizations that operate to specifications put forth by the team. Up-stream processes provide inputs to the team's organization. Down-stream processes provide or manage outputs from the team's organization.

In defining the life cycle, begin by identifying in-house processes and associated material and energy consumed and wasted by each process. It may be appropriate to designate types of materials, such as solvents, as opposed to specific material types, such as xylene, for each process. This will still allow the team to identify desired technologies such as water-based solvents. Then, the evaluation should move up- and down-stream by answering three questions:

- What specific company or operation or type of company or operation produces the material and energy consumed?
- Is the product used in the general marketplace? Or, if not, what specific person, company, or operation uses the product?
- Other than the product flowing to another life cycle process, are materials and energy output from the process generally recoverable or treatable?

Such questions will help the evaluation (1) identify up- and down-stream processes and (2) determine who is involved and whether specific or more general processes are relevant within each life cycle stage. As each up- and down-stream process is identified, the questions should be repeated. As the process proceeds, the team should note:

- the transition between life cycle stages,
- the desired and undesirable technology types, and
- any materials that are obviously linked to specific requirements or goals.

Such a collection of processes and associated inputs and outputs is called an *inventory*.

Inventory information about specific processes can often be found in facility process and environmental engineering records, purchasing and waste management records, and other information and assessment systems. More general information can be found in engineering, scientific, and industry literature to represent (1) general marketplaces and (2) specific companies, operations, or locations when information is not readily available[2]. General reference books include *Kirk-Othmer Encyclopedia of Chemical Technology* or the *Encyclopedia of Processing and Design*. These sources provide process descriptions, raw material consumption, and utility requirements generally in the form of industry averages for a wide range of industrial and recovery processes. Within the preliminary assessment, these information sources should be scanned with the purpose of capturing desirable and non-desirable technology types within each life cycle stage.

Worksheet 3: Defining the Technology Life Cycles in each of the attachments provides a template to present life cycle processes for the preliminary assessment. Arrows designating product and process feeds should link the processes, depicted in boxes. Additional detail such as regulated and recoverable materials, energy consumption, and prominent wastes may be included if readily available. Such a worksheet is completed for each option being considered.

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[2] For example, when such information is not routinely collected, neatly maintained, or is considered proprietary.

2.2.2 Linking Technologies to Requirements and Goals

Once the life cycle of each technology has been defined, each should be assessed with respect to the requirements and goals. In this way, technologies that do not meet requirements and other clearly inferior can be eliminated.

Worksheet 4 in each of the attachments, *Linking Technologies to Requirements and Goals*, provides a systematic method to screen technologies. The first step in completing this worksheet is to list possible technologies and associated categories and desirable technology types prominent throughout the life cycle. Next and referring to each technology inventory, the *status of achievement* for technologies for each requirement or goal should be determined as follows:

+	if the technology meets each requirement or goal
-	if the technology does not meet each requirement or goal
?	if more information is needed to determine if the technology meets or does not meet each requirement or goal

The team may also decide to obtain additional information for technologies that appear promising as required to complete the matrix.

2.2.3 Linking Options to Requirements and Goals

The degree to which each option lends to the achievement of requirements and goals should be assessed. *Worksheet 5: Linking Options to Requirements and Goals* provides a template to assess life cycle options as to their achievement of requirements and goals. The degree of achievement of options are rated as follows:

E	Option considerably EXCEEDS the requirement or goal.
M	Option MEETS the requirement or goal without considerably exceeding it.
FS	Option FAILS to meet the requirement or goal by a SLIGHT margin.
FC	Option FAILS to meet the requirement or goal by a CONSIDERABLE margin.
?	More information is needed to determine if the achievement of the option.

Options that do not meet requirements and other clearly inferior options should be eliminated. *Preferred Engineering Options* (PEOs), those that meet requirements at a minimum and meet several goals at best, should be retained for further assessment. The evaluation may also decide to obtain additional information for options that appear promising as required to complete the matrix.

2.3 Detailed Assessment

To this point, the PEOs have been defined through requirements and goals aimed environmental implications at the facility, local, regional, and global levels. The evaluation has been guided by improvement strategies ranging from source reduction, recovery, and treatment throughout the life cycle.

2.3.1 Retargeting the Assessment

The evaluation now must refine their concepts and take the PEOs from concept through implementation. The intended use of the information is the development of engineering specifications that refine PEOs. This entails creating a record that stipulates how to configure, produce, purchase and manage materials, operate, and distribute, and how to facilitate preferable disposition practices.

The purpose of the detailed assessment can be defined by revisiting the environmental requirements and goals. Table 2.4 illustrates how requirements and goals can be linked to impacts, and undesirable and desirable technologies through a *Requirement-Impact-Technology Network.*

Table 2.4 Requirement-Impact-Technology Networks

Requirement or Goal	Impact	Undesirable Technologies	Desirable Technologies
Minimize or eliminate the use and waste of toxic materials throughout the life cycle.	illness or death	• heavy metals • toxic acids • PBTs • etc.	• non-toxic materials
Maximize the recovery of materials throughout the life cycle.	resource depletion	• thermosets • unrecoverable solvents • unrecoverable metals • etc.	• thermoplastics • recoverable solvents • recoverable metals • etc.
Reduce or eliminate the use of chemicals linked to global warming throughout the life cycle.	global warming	• energy inefficient equipment • CFCs • HCFCs • VOCs • etc.	• energy efficient equipment • materials of low energy content • etc.

The evaluation should recognize that a complete set of life cycle information for the inventory or any requirement-impact-technology network, including all material and energy input and output from all life cycle processes and how each input and output contributes to impacts to human health and the environment, is not readily available and varies in quality. Furthermore, the information that is available can be difficult to manage and appropriately allocate to processes within the life cycle.

A detailed LCE assessment includes (1) refining the inventory of life cycle processes and related information, (2) assessing impacts through requirements and goals linked to each technology inventory, and (3) identifying and addressing the sources of any concerns. The evaluation can employ available Life Cycle Assessment and/ or Design for Environment software and other tools as listed in Section 7.3 or use a simple set of spreadsheets to manage detailed assessment information, through a series of interconnected spreadsheets, as illustrated in Figure 2.2 and described below.

2.3.2 Redefining the Technology Life Cycles

Defining desirable and undesirable technologies should help guide the redefinition of each technology life cycle. Broadly-defined processes within the life cycle should be subdivided if

(1) specific desirable or undesirable technologies will be better understood by doing so or (2) if the broadly-defined process is not well understood.

Again general references such as *Kirk-Othmer Encyclopedia of Chemical Technology* or the *Encyclopedia of Processing and Design* can be used to obtain inventory information. Additional information may be found in subject-specific resources such as the *Handbook for Petrochemical Processes*, The USEPA's *Industrial Process Profiles for Environmental Use*, or the *Environmental Sources and Emissions Handbook.* Again information is provided as industry averages or averages from a number of monitored plants. Searches for reports, articles, or other sources can be used to fill the remaining information gaps. These searches can include USEPA reports and industry or trade magazines. Additional resources are listed in Section 7.1.

As illustrated in Figure 2.2 and described in Table 2.5, a spreadsheet may be used to capture each *technology inventory* with the inventory components in each row and the life cycle stages and processes as the column designations. Then, a *technology inventory summary* can be used to combine processes over the life cycle of each technology with the inventory components in each row and the technologies as the column designations. Then, technologies can be combined, by calculating the functional equivalent of each technology for each option, in an *option inventory.*

Figure 2.2 The Detailed Assessment Process

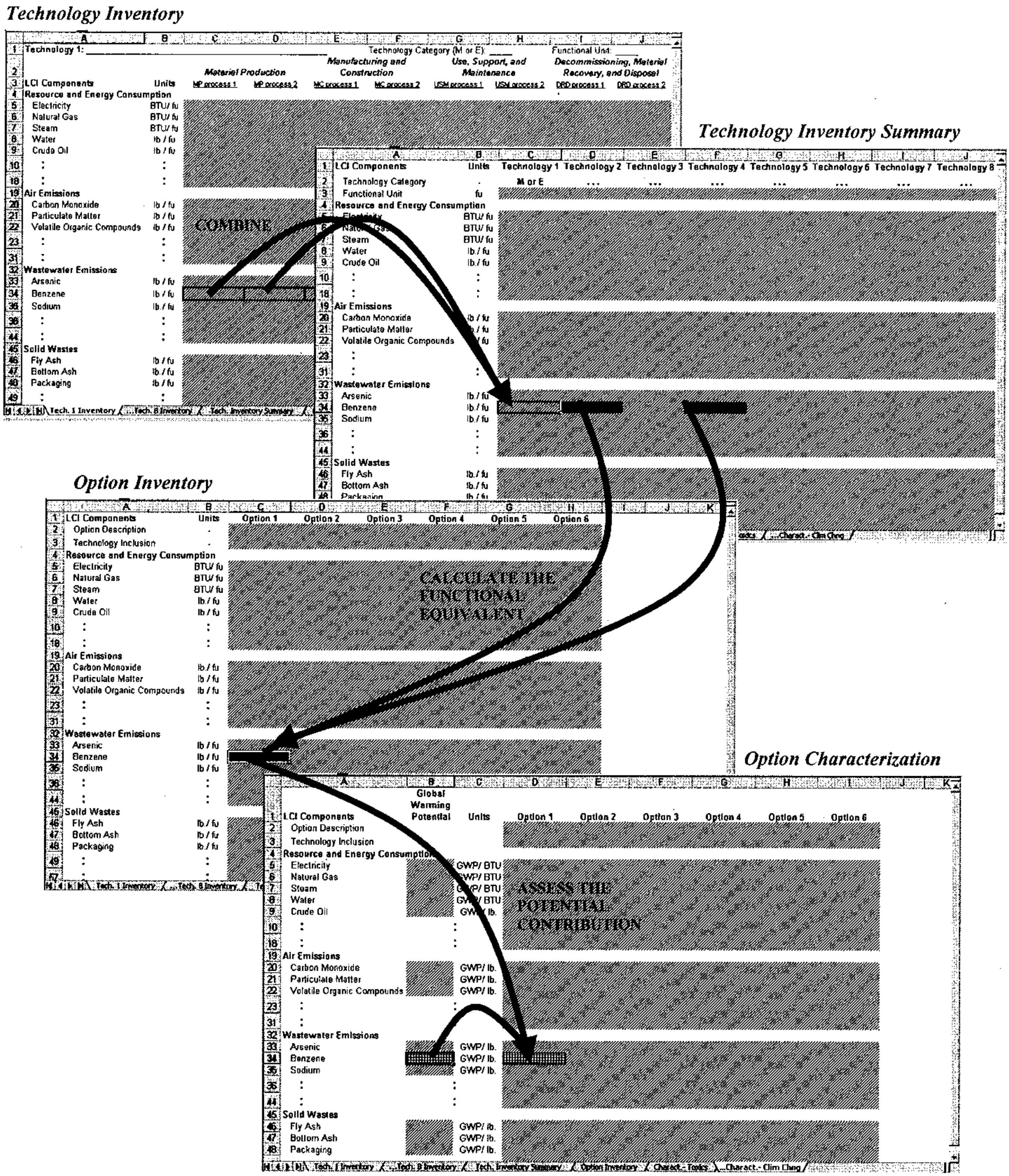


Table 2.5 Detailed Assessment Spreadsheets

Redefinition Process Step	Row Designations	Column Designations	Sheet Contents	Spreadsheet Coverage
Technology Inventory	inventory components	processes by life cycle stage	process-specific inputs and outputs	one per technology
Technology Inventory Summary	inventory components	technologies	technology-specific inputs and outputs	one for all technologies
Option Inventory	inventory components	options	option-specific inputs and outputs	one for all options
Option Characterization	inventory components	options	contribution of options to impacts	one per impact

2.3.3 Reassessing Requirements and Goals

Detailed performance and cost assessments should be performed in a manner that applies sound engineering and economic principles, is compatible with company policies, and explicitly links to associated requirements and goals. For environmental requirements and goals, impact-specific equivalency. factors can be applied to each inventory component in an impact-specific *option characterization worksheet* as shown in Figure 2.2. Impact specific equivalency factors, as listed in Table 2.6, provide a relative measure to assess the potential contribution of specific technologies to specific impacts. Additional information concerning equivalency factors can be found in the resources listed in Section 7.2.

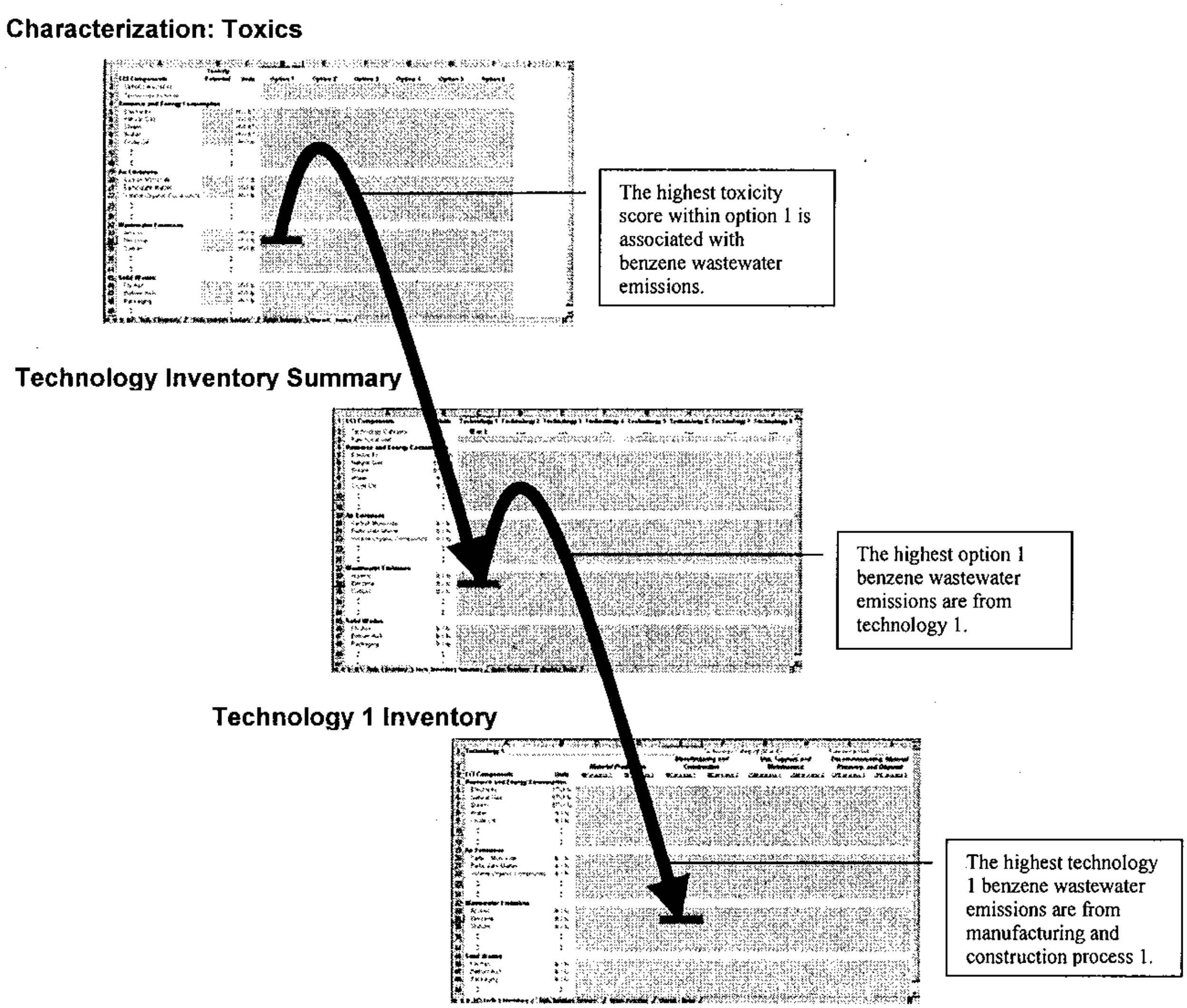
Table 2.6 Assessing the Potential Contribution of Inventory Components to Specific Impacts

Requirement or Goal	Impact	Example Equivalency Factors
Minimize or eliminate the use and waste of toxic materials throughout the life cycle.	illness or death	• mass or volume of toxic materials • toxicity hazard values • critical volumes
Maximize the recovery of materials throughout the life cycle.	resource depletion	• percent recovered mass • percent recoverable mass
Reduce or eliminate the use of chemicals linked to global warming throughout the life cycle.	global warming	• global warming potentials • ozone depletion potentials

2.3.4 Identifying Key Technologies

For performance, cost, and environmental requirements, backtracking through well-structured and documented assessments will aid in the identification of key contributing technologies. Figure 2.3 illustrates backtracking using the detailed environmental assessment spreadsheets. The resulting set of key technologies can be desirable, in which case the evaluation may seek to increase their use. Alternatively, key technologies might be undesirable, in which case the team may seek to eliminate or reduce their use.

Figure 2.3 Environmental Assessment Process Backtracking



2.4 Developing Specifications

Using the set of LCE activity categories presented in Figure 1.3 as a guide, the evaluation team can assess the applicability of activities to each key technology. At this point in the engineering process, it will be more difficult, but not always impossible, to change the materials or equipment that made it through the preliminary assessment. Team efforts might focus on identifying opportunities to specify more efficient processes/pollution prevention opportunities throughout the life cycle. For example, an innovative elimination or recovery technology used in manufacturing might also be useful in material production or maintenance activities and could be specified through (1) procurement activities and (2) maintenance procedures.

In cases where the evaluation team must and cannot easily prioritize activities, they may seek to include a valuation step. Valuation is the process of assigning values or relative weights to the various impacts or requirements and goals. Valuation methods are described in several of the resources in Section 7.3.

In the following sections a number of case studies are presented to illustrate the application of the LCE framework and process. Because the studies themselves were conducted prior to the LCE procedure being developed and in many cases without specifically considering all of the elements of LCE, there will be some information gaps.

3. Maintenance

This section describes the consideration of life cycle environmental factors in the routine, scheduled, and unanticipated maintenance of existing systems, processes, or facilities.

3.1 Products and Systems

For many products and systems that are durable in nature, the activities associated with their maintenance and upkeep can produce a larger environmental footprint than the operations associated with their original production. Understanding the differential contributions of the maintenance portion of the product or system life cycle relative to the production activity is often key in making engineering decisions associated with durability, serviceability, and ownership cost. For new products or systems, the LCE process applicable to the maintenance stage is discussed in Section 5. For existing products or systems, within the maintenance stage itself, decisions made regarding the procedures, technologies, and materials still have life cycle implications. Careful consideration of improvements at this point can lead to substantial improvements in the product or system life cycle profile.

3.2 Processes and Facilities

Maintenance processes comprise a set of activities designed to support products after placing them in use, permitting them to function at a high level of performance for an extended period. Maintenance activities are also embedded in the operations associated with manufacturing and service facilities. Because maintenance is such a frequent activity, the environmental burdens from these activities can be substantial. In some instances redesign of maintenance processes and facilities can be as beneficial in reducing impacts as product redesign.

3.3 LCE Case Study: Chemical Agent Resistant Coatings

Chemical Agent Resistant Coatings (CARC) are specialized barrier materials applied to various pieces of military equipment including combat and ground support vehicles used by the U.S. Army. Historically, CARC has consisted of a specific type of paint, applied to the vehicle with a spray gun in a paint spray booth. The LCE CARC Project (USEPA, 1996) comprised a life cycle assessment-oriented project to assess the potential environmental benefits of an alternative CARC system, to be used during vehicle maintenance operations, together with performance and cost analysis components.

3.3.1 Targeting the Evaluation

Establishing the Function being Provided

The function of CARC, as the name implies, is to minimize the surface adhesion and cross-contamination caused by enemy deployment of chemicals on the battlefield. If inhaled or ingested by soldiers or maintenance personnel these could be incapacitating or fatal. CARC acts as a barrier between the chemical and the metal or polymeric components of the vehicle to permit the rapid and complete removal of any chemical agent from the surface.

Naming an Evaluation Team

The evaluation team for this effort consisted of several distinct groups. Members of the team included:

- U.S. Army maintenance facility staff and supervisory personnel at the Army's Transportation Center at Fort Eustis, Virginia who were thoroughly familiar with the operational and performance aspects of CARC use and disposition.
- Environmental specialists whose responsibility was to identify the characteristics of the CARC system that had the potential to create adverse environmental impacts and to analyze various alternatives
- Coatings engineers whose function was to identify the available alternative materials and to set up tests to establish their relative performance against a set of well-defined criteria and to analyze the costs of the various options
- Life cycle process engineers who were responsible for establishing the system boundaries, identifying and collecting process information on the upstream materials production, and characterizing the waste management aspects of the coatings operation.

These groups interacted on a number of occasions during the course of the analysis, but could not function as an entirely integrated team due to geographic and resource limitations. The latter three groups formed the primary LCE team.

Developing Requirements and Goals

Requirements for the process upgrade with respect to the coating materials themselves – primer and thinner primarily – were influenced by a number of factors. Some inherent constraints were imposed by the certification status of the CARC materials (i.e. MIL-STD compliance) and some were associated with the time frame for the project, i.e. short term implementation of new but commercial technology versus a long term R, D & D effort. Details on these requirements and goals may be found in Table 3.1 which is an excerpt of *Routine and Unanticipated Maintenance Worksheet 1*. Additional requirements (R) and goals (G), consisting of a mix of performance, cost, and environmental aspects, were identified as well. Although the performance and cost aspects are generally confined to the life cycle stage where the system is used and maintained, the environmental requirements and goals are associated with benefits and impacts that accrue over the upstream and downstream stages as well as the in-house activities.

Table 3.1 CARC Requirements and Goals

Category	Applicable Life Cycle Stage				Requirements and Goals	Requirement (R) or Goal (G)
	MP	MC	USM	D		
Performance						
Chemical (compatibility)			X		Must not cause corrosion of vehicle surface or spray gun	R
Mechanical			X		Acceptable surface quality as defined by performance test	R
Mechanical			X		Improved transfer efficiency	G
Physical			X		Stainless steel application equipment to prevent corrosion	R
Thermal			X		No or minimal temperature or humidity effects on cure rate	R
Cost						
Materials			X		Lower cost for topcoat, primer and thinner	G
Materials			X		Reduced labor costs compared with baseline	G
Equipment			X		Lower costs for spray guns	G
Waste management			X	X	Reduced costs for waste disposal	G
Environmental – Facility						
Hazmat management and waste			X	X	Reduce or eliminate generation of waste solvents/solvent-containing paint	R
Energy consumption	X	X	X		Less than baseline	G
Environmental – Local						
Photochemical smog production	X	X	X		Reduce VOC emissions	R
Water pollution			X		Less solvent and pigment discharges to sewer	G
Toxic materials in the environment	X	X	X	X	Reduce solvent and metal-bearing pigment releases	R
Landfill space			X	X	Decreased solid waste generation	G
Environmental – Regional						
Visibility impairment			X		Reduce the amount of particulates released	G
Environmental- Global						
Resource conservation	X	X	X	X	Reduced fuels consumption	G

Typically, the set of requirements and goals should be the minimum set necessary to realize the optimal combination of system attributes. Constraints may be added to this minimum set but unless these are requirements set by regulatory or other low discretion drivers, the added criteria may simply serve to complicate the assessment.

Proposing Engineering Technologies and Options

Given the identified set of requirements and goals, the evaluation team was able to specify seven different technologies: 2 primers, 2 thinners, 2 types of application equipment, and a bath recovery system. These are listed in Table 3.2, an excerpt from *Routine and Unanticipated Maintenance Worksheet 2.*

Table 3.2 CARC Technology Information

Technology Name	Description	Technology Category*	Desirable Technology Types**
1. MIL-P53022	solvent-based epoxy primer	M	NREG
2. MIL-P53030	water-thinable epoxy primer	M	NREG
3. MIL-T81772	standard thinner	M	T
4. AA-857-B	alternative thinner	M	T
5. Std. spray gun	high-pressure, low-volume standard (conversion zone) spray gun	E	TW
6. Alt. spray gun	high-volume, low pressure turbine spray gun (Can-Am)	E	ME, TW
7. Alt. gun bath	spray gun bath with recycling feature	E	ME, TW

***Technology Categories**
- material (M)
- equipment (E)

****Desirable Technology Types:**
- *materials:* non-regulated (NREG), non-contributory (NC), non-energy intensive (NEI), non-water intensive (NWI), recoverable (REC), treatable as waste (T)
- *equipment:*: material efficient (ME), energy efficient (EE), water efficient (WE), material recovery (MR), energy recovery (ER), treatable wastes (TW)

The primer technologies include a water-thinable primer in lieu of the solvent-based material currently used. The thinner technologies include an alternative paint thinner substitute for the current baseline thinner. The equipment technologies represent modifications – a substitution of a different spray gun for the currently used item and the acquisition of a new bath for cleaning of the spray guns on a daily basis with recovery and reuse of the bath solvent. Additional aspects, including spray booth configuration, filtration systems, and material storage, were not considered as separate alternatives due to issues of site-specificity. Similarly, the current blast media and depainting technology were deemed cost-effective and environmentally acceptable and therefore were not subject to evaluation.

Options considered to be potentially attractive included various combinations of CARC topcoat, primer, and application technologies (spray guns) that increase materials use efficiency and decrease the time involved in painting operations. To create a functional CARC coating system, various combinations of technologies were assembled as shown in Table 3.3, an excerpt from *Routine and Unanticipated Maintenance Worksheet 2.* The first five system options consist of assemblies of alternative primer, thinner, and spray gun while the last option is potentially useable in combination with any of the other options. Each option was evaluated as to the degree to which it was estimated to achieve or fail to achieve the requirements and goals across the life cycle. Also, the alternative spray gun was noted to be slightly easier to maintain, as indicated by the "simplified" configuration status. Obviously, the assessments at this point were based on limited information and should be considered valid only for screening purposes.

Table 3.3 CARC Inclusion of Technologies

Option Name	Technology 1 MIL-P53022	Technology 2 MIL-P53030	Technology 3 MIL-T81772	Technology 4 AA-857-B	Technology 5 Std. spray gun	Technology 6 Alt. spray gun	Technology 7 Alt. gun bath	Topcoat
UNITS	gal	gal	gal	gal	pc	pc	pc	gal
1. Alternative primer; std. gun, topcoat and thinner		2.50	1.63		1			5.00
2. Can-Am turbine HVLP spray gun; standard topcoat, thinner and primer	1.81		1.63			1		3.66
3. Alternative primer; std. topcoat and thinner; alternative gun		1.81	1.63			1		3.66
4. Alternative thinner; standard topcoat, primer and spray gun.	1.81			1.63	1			5.00
5. Alternative primer and thinner; standard topcoat and spray gun		1.81		1.63	1			5.00
6. Alternative spray gun bath							1	NA
CONFIGURATION STATUS simplified (SIMP), accessible (ACC), modular (MOD), joining status (JS)						SIMP		

3.3.2 Preliminary Assessment

Defining the Technology Life Cycles

Figures 3.1 a - f, which are from *Routine and Unanticipated Maintenance Worksheet 3*, shows the life cycle activities and material/energy flows associated with each of the technologies. Because several of the environmental and one of the cost criteria span more than the use and maintenance life cycle stage, the LCE framework requires the description and consideration of the whole life cycle.

Figure 3.1a CARC Technology 1: MIL-P53022 Primer

Technology	Technology 1: MIL-P53022 primer
Additional material and equipment requirements	• Topcoat • MIL-T81772 **OR** AA-857-B Thinner • Standard HVLP spray gun with associated compressor/air supply and spray booth with applicable air quality control equipment; equipment manufacturing, building and site requirements were included in costs only. **OR** Turbine HVLP spray gun with associated compressor/ air supply (72 hp.) and spray booth with applicable air quality control equipment; equipment manufacturing, building and site requirements were included in costs only.
Maintenance procedures	In accordance with standard Army protocols and technical orders and manufacturer's MSDS and other applicable literature.

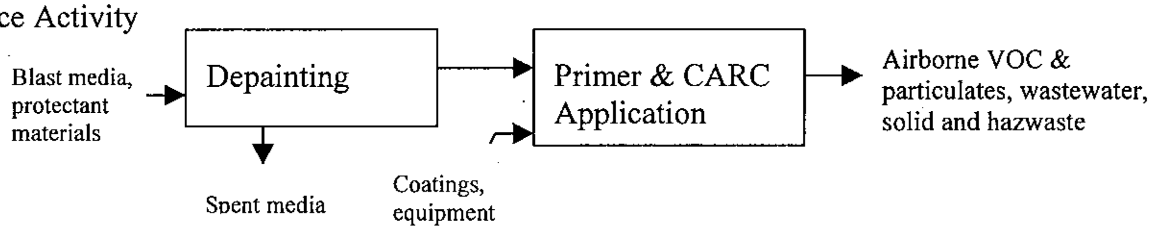
Material Production

MIL-P53022 primer consists of two technologies – a resin and a curing agent. The materials production stage modules are depicted in the attached process flow sheets.

Technology Manufacturing

Not applicable to this technology.

Maintenance Activity



Material Recovery and Disposal

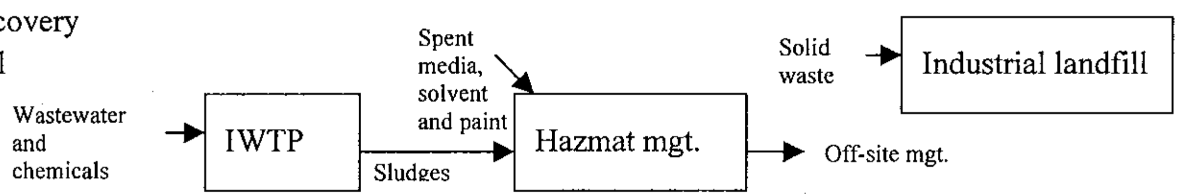


Figure 3.1b CARC Technology 2: MIL-P53030 Primer

Technology	Technology 2: MIL-P53030 primer
Additional material and equipment requirements	• Topcoat • MIL-T81772 **OR** AA-857-B Thinner • Standard HVLP spray gun with associated compressor/air supply and spray booth with applicable air quality control equipment; equipment manufacturing, building and site requirements were included in costs only. **OR** Turbine HVLP spray gun with associated compressor/ air supply (72 hp.) and spray booth with applicable air quality control equipment; equipment manufacturing, building and site requirements were included in costs only.
Maintenance procedures	In accordance with standard Army protocols and technical orders and manufacturer's MSDS and other applicable literature.

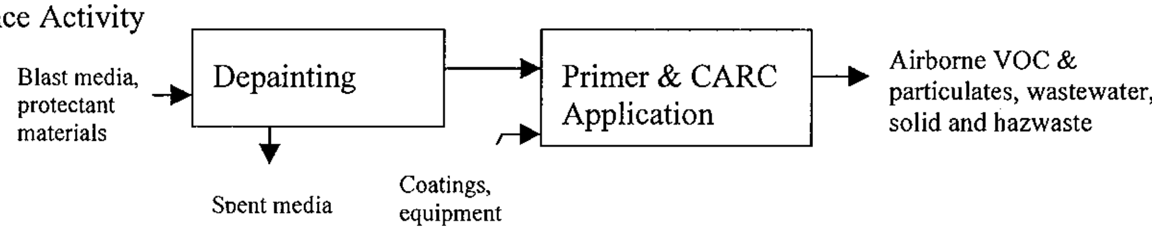
Material Production

MIL-P53030 primer consists of two technologies – a resin and a curing agent. The materials production stage modules are depicted in the attached process flow sheets.

Technology Manufacturing

Not applicable to this technology.

Maintenance Activity



Material Recovery and Disposal

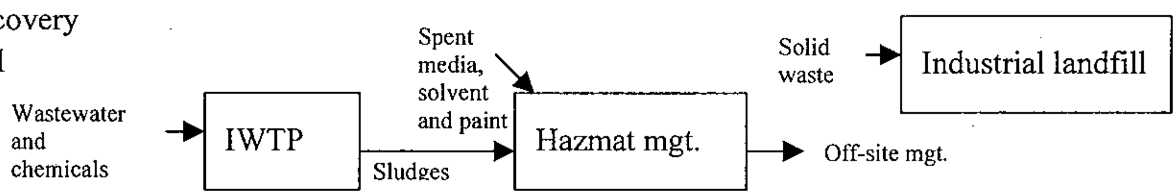


Figure 3.1c CARC Technology 3: MIL-T81772 Thinner

Technology	Technology 3: MIL-T81772 Thinner
Additional material and equipment requirements	• Topcoat • MIL-P53022 **OR** MIL-53030 primer • Standard HVLP spray gun with associated compressor/air supply and spray booth with applicable air quality control equipment; equipment manufacturing, building and site requirements were included in costs only. **OR** Turbine HVLP spray gun with associated compressor/ air supply (72 hp.) and spray booth with applicable air quality control equipment; equipment manufacturing, building and site requirements were included in costs only.
Maintenance procedures	In accordance with standard Army protocols and technical orders and manufacturer's MSDS and other applicable literature.

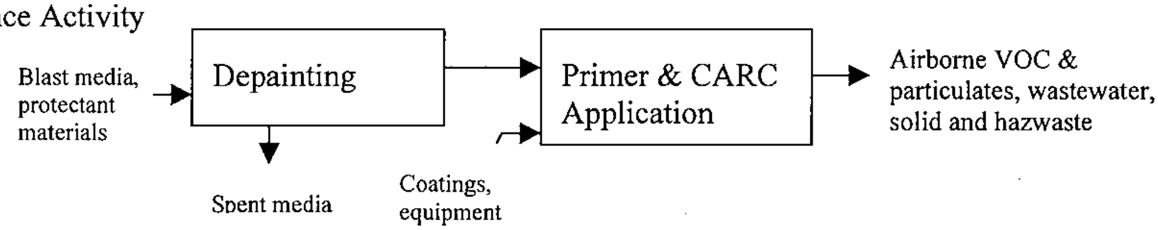
Material Production

The materials production stage modules are depicted in the attached process flow sheets.

Technology Manufacturing

Not applicable to this technology.

Maintenance Activity



Material Recovery and Disposal

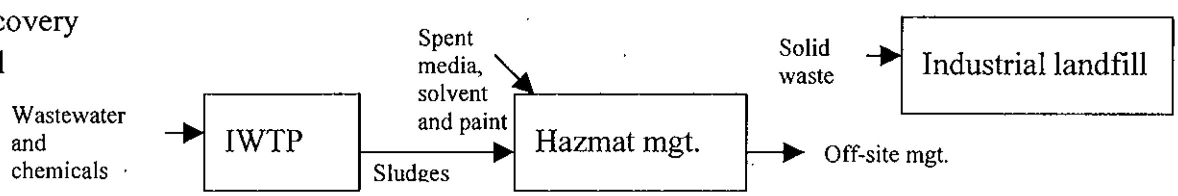


Figure 3.1d CARC Technology 4: AA-857B Thinner

Technology	Technology 4: AA-857B Thinner
Additional material and equipment requirements	• Topcoat • MIL-P53022 **OR** MIL-53030 primer • Standard HVLP spray gun with associated compressor/air supply and spray booth with applicable air quality control equipment; equipment manufacturing, building and site requirements were included in costs only. **OR** Turbine HVLP spray gun with associated compressor/ air supply (72 hp.) and spray booth with applicable air quality control equipment; equipment manufacturing, building and site requirements were included in costs only.
Maintenance procedures	In accordance with standard Army protocols and technical orders and manufacturer's MSDS and other applicable literature.

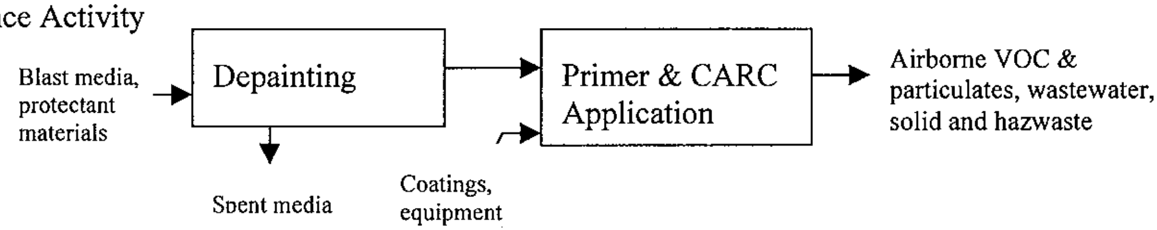
Material Production

The materials production stage modules are depicted in the attached process flow sheets.

Technology Manufacturing

Not applicable to this technology.

Maintenance Activity



Material Recovery and Disposal

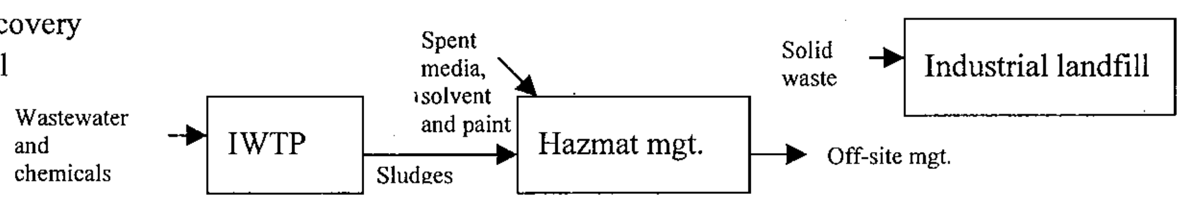


Figure 3.1e CARC Technology 5: Standard HVLP spray gun

Technology	Technology 5: Standard HVLP spray gun with associated compressor/air supply and spray booth with applicable air quality control equipment; equipment manufacturing, building and site requirements were included in costs only.
Additional material and equipment requirements	• Topcoat • MIL-T81772 **OR** AA-857B Thinner • MIL-P53022 **OR** MIL-53030 primer
Maintenance procedures	In accordance with standard Army protocols and technical orders and manufacturer's MSDS and other applicable literature.

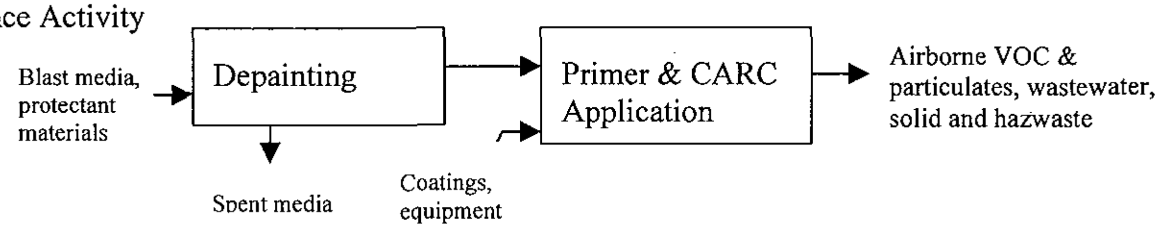
Material Production

Not applicable to this technology.

Technology Manufacturing

In accordance with accepted LCA practice, this technology excludes the upstream burdens associated with manufacturing the alternative spray gun and associated equipment. Differences between the manufacturing of the standard HVLP gun and the alternative are insignificant.

Maintenance Activity



Material Recovery and Disposal

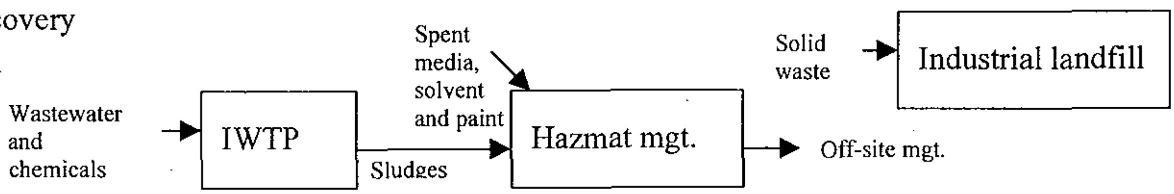


Figure 3.1f CARC Technology 6: Turbine HVLP spray gun

Technology	Technology 6: Turbine HVLP spray gun with associated compressor/ air supply (72 hp.) and spray booth with applicable air quality control equipment; equipment manufacturing, building and site requirements were included in costs only.
Additional material and equipment requirements	• Topcoat • MIL-T81772 **OR** AA-857B Thinner • MIL-P53022 **OR** MIL-53030 primer
Maintenance procedures	In accordance with standard Army protocols and technical orders and manufacturer's MSDS and other applicable literature.

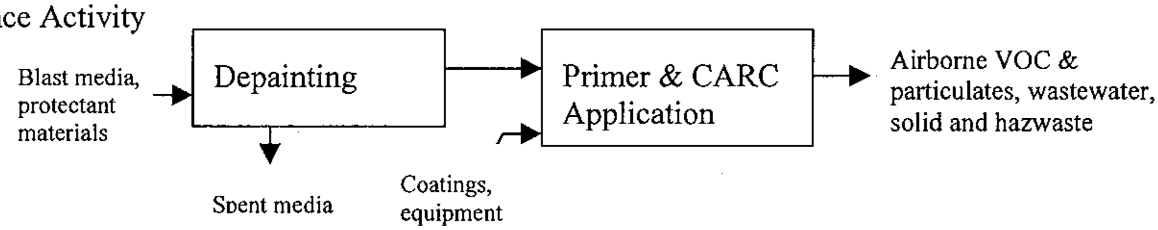
Material Production

Not applicable to this technology.

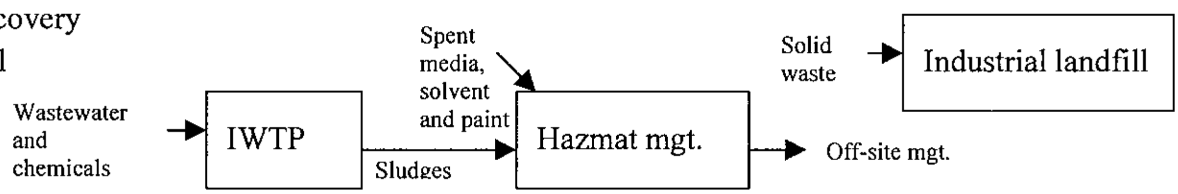
Technology Manufacturing

In accordance with accepted LCA practice, this technology excludes the upstream burdens associated with manufacturing the alternative spray gun and associated equipment. Differences between the manufacturing of the standard HVLP gun and the alternative are insignificant.

Maintenance Activity



Material Recovery and Disposal



Linking Technologies to Requirements and Goals

Table 3.4, which is from *Routine and Unanticipated Maintenance Worksheet 4*, shows the status of achievement each of the technologies with respect to the requirements and goals. Each of the technologies was individually evaluated against the criteria using the readily available information and the knowledge of the evaluation team. The purpose of this initial analysis was to qualify technologies for further assessment and focus attention on those with the greatest potential for attaining the requirements and goals. Based on the initial review the alternative primer, thinner, and spray gun technologies (Technologies 2, 4, and 6) all looked relatively attractive for configuring system options.

Table 3.4 CARC Technologies Status of Achievement

Requirements and Goals	Req't (R) or Goal (G)	Technology 1 MIL-P53022	Technology 2 MIL-P53030	Technology 3 MIL-T81772	Technology 4 AA-857-B	Technology 5 Std. spray gun	Technology 6 Alt. spray gun	Technology 7 Alt. gun bath	COUNT +/-
Performance									
P1. Must not cause corrosion of vehicle or spray gun	R	+	+	+	+	+	+	?	5/0
P2. Acceptable surface quality as determined by test	R	+	+	+	+	+	+	-	5/1
P3. Improved transfer efficiency	G	?	?	?	?	-	+	-	1/2
P4. Stainless steel materials of construction	R	NA	NA	NA	NA	?	+	?	1/0
P5. No or minimal humidity effects on cure rate	R	+	+	+	+	NA	NA	NA	4/0
Cost									
C1. Lower topcoat, primer and thinner cost	G	-	+	-	-	-	+	NA	3/4
C2. Reduced cost of labor	G	-	+	-	-	-	?	?	1/4
C3. Lower costs for spray guns	G	NA	NA	NA	NA	-	-	-	1/3
C4. Reduced waste disposal cost	G	-	-	-	-	-	+	+	2/5
Environmental - Facility									
EF1. Reduce or eliminate solvent emissions	G	-	+	-	+	-	+	?	3/3
EF2. Reduce energy consumption	G	-	+	-	+	-	+	+	4/3
Environmental -Local									
EL1. Reduce VOC emissions	R	-	+	-	+	-	+	-	3/4
EL2. Less solvent and pigment discharges to sewer	G	-	+	-	+	-	+	+	4/3
EL3. Reduce solvent/metal-bearing pigment releases	R	-	+	-	+	-	+	-	3/4
EL4. Decreased solid waste generation	G	-	-	-	-	-	?	?	0/5
Environmental - Regional									
ER1. Reduce the amount of particulates released	G	-	-	-	-	-	+	?	1/5
Environmental - Global									
EG1. Reduced fuels consumption	G	-	+	-	+	-	+	?	3/3
COUNT + REQUIREMENTS / GOALS		3/1	5/6	3/0	5/4	3/0	6/9	0/4	
COUNT - REQUIREMENTS / GOALS		2/9	0/3	2/9	0/5	2/9	0/1	4/2	

Linking Options to Requirements and Goals

Table 3.5, which is from *Routine and Unanticipated Maintenance Worksheet 4*, shows the degree of achievement of each of the option with respect to the requirements and goals. At this juncture the two CARC technology options that appeared most attractive were the following:

- The alternative spray gun (Option 2) based on meeting 5 of the 6 requirements and 4 of the 11 goals.
- The alternative spray gun and primer combination (Option 3) based on meeting or exceeding 5 of the 6 requirements and meeting 4 of the 8 goals.
- The other technology options (1, 4, and 5) were retained for further consideration, but at a lower priority.

The cleaning bath option (Option 6) was dropped from further consideration due to a low performance potential and a significant gap in information.

Table 3.5 CARC Options Degree of Achievement

Requirements and Goals	Req't (R) or Goal (G)	Option 1 Alternative primer, std. gun, topcoat and thinner	Option 2 Can-Am turbine HVLP spray gun; standard topcoat, thinner and primer	Option 3 Alternative primer, std. topcoat and thinner, alternative gun	Option 4 Alternative thinner, standard topcoat, primer and spray gun.	Option 5 Alternative primer and thinner, standard topcoat and spray gun	Option 6 Alternative spray gun bath
Performance							
P1. Must not cause corrosion of vehicle/spray gun	R	M	M	M	M	M	?
P2. Acceptable surface quality (by test)	R	M	M	M	M	M	NA
P3. Improved transfer efficiency	G	FS	E	E	?	?	NA
P4. Stainless steel materials of construction	R	?	M	M	?	?	?
P5. No or minimal humidity effects on cure rate	R	M	M	M	M	M	NA
Cost							
C1. Lower topcoat, primer and thinner cost	G	FS	FS	M	FS	FS	NA
C2. Reduced cost of labor	G	FS	FS	?	FS	FS	?
C3. Lower costs for spray guns	G	FS	FC	FC	FS	FS	FS
C4. Reduced waste disposal cost	G	FS	?	E	FS	FS	M
Environmental - Facility							
EF1. Reduce or eliminate solvent emissions	G	FS	FS	M	FS	M	?
EF2. Reduce energy consumption	G	FS	E	E	FS	M	M
Environmental – Local							
EL1. Reduce VOC emissions	R	E	FS	E	FS	E	FS
EL2. Less solvent and pigment discharges to sewer	G	FS	FS	E	FS	E	M
EL3. Reduce solvent/metal-bearing pigment releases	R	FS	M	M	FS	M	M
EL4. Decreased solid waste generation	G	FS	?	?	FS	FS	?
Environmental - Regional							

Requirements and Goals	Req't (R) or Goal (G)	Option 1 Alternative primer, std. gun, topcoat and thinner	Option 2 Can-Am turbine HVLP spray gun; standard topcoat, thinner and primer	Option 3 Alternative primer; std. topcoat and thinner, alternative gun	Option 4 Alternative thinner; standard topcoat, primer and spray gun.	Option 5 Alternative primer and thinner, standard topcoat and spray gun	Option 6 Alternative spray gun bath
ER1. Reduce the amount of particulates released	G	FS	FS	M	FS	FS	?
Environmental – Global							
EG1. Reduced fuels consumption	G	FS	?	M	FS	M	?
COUNT E REQUIREMENTS/GOALS		1/0	0/1	1/3	0/0	1/1	0/0
COUNT M REQUIREMENTS/GOALS		3/0	5/4	5/4	3/0	4/3	1/3
COUNT FS REQUIREMENTS/GOALS		1/11	1/5	0/0	2/10	0/6	1/1
COUNT FC REQUIREMENTS/GOALS		0/0	0/1	0/1	0/0	0/0	0/0

Key:

- E — Option considerably EXCEEDS the requirement or goal.
- M — Option MEETS the requirement or goal without considerably exceeding it.
- FS — Option FAILS to meet the requirement or goal by a SLIGHT margin.
- FC — Option FAILS to meet the requirement or goal by a CONSIDERABLE margin.
- ? — More information is needed to determine the achievement status of the option.

3.3.3 Detailed Assessment

Retargeting the Assessment

The detailed assessment stage consisted of performance, cost, and environmental aspects. Performance characteristics were addressed through a set of scored criteria. The economic analyses were based on costs in dollars for depainting and painting one functional unit at Ft. Eustis, Virginia.

Environmental requirements and goals were analyzed using a Life Cycle Impact Assessment directed at résource and energy consumption, environmental burdens and waste generation. The environmental evaluation of the selected options consisted of performing a life cycle assessment (LCA) on each of the options considered to provide potential improvements. Each option's analysis consisted of a life cycle inventory to measure the energy and materials flows for the topcoat, primer, and thinner manufacturing, use, and final disposition. The manufacturing of the capital equipment (buildings, spray guns and compressors, etc.) was not included in this analysis in keeping with standard LCA practice. Exclusion of the energy, materials, and wastes associated with manufacturing the equipment and the associated materials of construction is usually justified by the small amount of each item's lifetime consumed in delivering the functional unit specified, in this case 1000 ft^2 of coated surface.

The CARC Requirement-Impact-Technology Networks are shown in Table 3.6. Based on the relationships identified, the life cycle inventory and impact assessment effort could be focused on collecting appropriate information for a limited number of options.

Table 3.6 CARC Requirement-Impact-Technology Networks

Environmental Requirement or Goal	Impact	Undesirable Technologies	
Environmental- Facility			
EF1. Reduced generation of waste solvents and paints (improved hazardous material management)	Human and terrestrial and aquatic fauna illness or death	• Ammonia • Benzene • carbon monoxide • chlorine • fluorine • formaldehyde • heavy metals	• hydrochloric acid • hydrogen cyanide • phenol • sulfuric acid • vinyl chloride • xylene • etc.
EF2. Reduced energy consumption	fuel resource depletion; impacts related to emissions	• energy inefficient equipment	• etc.
Environmental- Local			
EL1. Reduced VOC emissions	Smog formation	• acetaldehyde • toluene • benzene	• n-butane • n-octane • n-butyl acetate chloroform • etc.
EL2. Reduced solvent and pigment discharges to sewer	Aquatic species illness or death	• ammonia • benzene • heavy metals	• hydrochloric acid • phenol • sulfuric acid • etc.
EL3. Reduced solvent and metal-bearing pigment releases	Human and terrestrial and aquatic fauna illness or death	• ammonia • benzene • carbon monoxide • chlorine • fluorine • formaldehyde • heavy metals	• hydrochloric acid • hydrogen cyanide • phenol • sulfuric acid • vinyl chloride • xylene • etc.
EL4. Decreased solid waste generation	loss of habitats	• bottom ash • FGD solids • fly ash • hazardous and solid wastes	• plutonium • slag • uranium • etc.
Environmental- Regional			
ER1. Reduced particulate releases	Human and terrestrial fauna illness	• ammonia • fluorine • xylene • chlorine	• vinyl chloride • phenol • carbon monoxide • etc.
Environmental- Global			
EG1. Reduced fuels consumption (resource conservation)	Resource depletion, acid precipitation, climate change	• carbon dioxide • carbon tetrachloride • trichloroethane • sulfur oxides • nitrogen oxides • ammonia • hydrochloric acid • coal use	• iron ore use • magnesium ore use • petroleum use • thallium use • titanium use • water use • zinc use • etc.

Redefine the Technology Life Cycles

Reassessment of Performance, Cost, and Environmental Requirements and Goals

Several elements of performance were considered for each technology – application equipment surface quality and transfer efficiency; primer adhesion sensitivity due to surface cleanliness, temperature/humidity effects and cure rate, and thinner effectiveness and film characteristics. Details of the criteria and test procedures used for each criterion are described in the associated

LCA report (EPA, 1996). Performance criteria were not considered equivalent but were weighted by the evaluation team based on their relative importance within a given subcategory, e.g. surface quality.

The annualized costs analyzed in this assessment are those directly associated with the Army's internal operations. Both direct and indirect costs were included. Less well-defined costs, such as those associated with foregoing the best possible use of a resource, were excluded due to the difficulty in defining their magnitude. Cost analyses included both capital and operating costs for the selected options. A factored estimating approach was used that is expected to assess capital costs within +/- 40% and operating costs within +/- 30%. Additional details on the cost-related goals and requirements may be found in the CARC LCA report (EPA, 1996).

Results of the detailed annualized cost analysis (per 1000 ft^2) are summarized below; values in parentheses are the percentage of the total current baseline system cost:

Option 1: $2,966 (99.5%)

Option 2: $2,225 (67.9%)

Option 3: $2,611 (87.6%)

Option 4: $2,979 (99.9%)

Option 5: $2,963 (99.4%).

Based on this overall assessment, Options 2 and 3 appear to best meet the cost goals. Note that none of the options fully met the goal to reduce the cost of the spray guns.

The life cycle environmental assessment involved a life cycle inventory followed by a life cycle impact assessment (LCIA). In an LCIA the inventory information is converted into a number of indices of potential environmental impact.

Identification of Key Technologies

The primary technologies identified as key in identification of CARC system improvements are those materials manufacturing, use, and disposal operations associated with the primer and the use and disposal stage aspects of the alternative spray gun. If the options screening assessment had not fully identified the contributory technologies driving the environmental differences among the options, then the life cycle inventory data could have been used to prepare a technology inventory summary (Table 3.7). The summary highlights the relative contributing materials to the life cycle inventory and identifies points where alternative materials or processes may be beneficial for the team to consider.

In this study the life cycle inventory data were used to profile the options as combinations of material and equipment technologies. Since the performance and cost analysis favored Options 2 and 3, only those profiles are summarized (Table 3.8). If the engineering team is attempting to target specific materials with the project, then the option profile provides a comprehensive and quick way to assess the relative environmental performance of the available choices. For example, the team may have specified Class I Ozone Depleting Substances associated with cleaning, carbon dioxide emissions from process heating, or cadmium from electrical connector plating, for elimination or minimization. In the CARC system, CO_2 emissions from the two options are relatively similar (219 vs. 198 lb per functional unit coated), indicating that these technologies would not be especially contributory towards meeting that goal.

Table 3.7 Technology Inventory Summary				
		Technology 2	**Technology 4**	**Technology n ...**
		Alternative Primer	Alternative Thinner	
Technology category	M or E	M	M	
Functional Unit (FU)	lb/lb			
LCI Components				
Resource and Energy Consumption				
butyl acetate		0	0.31	
epoxy resin		0.24	0	
butyl alcohol		0.11	0	
zinc phosphate		0	0	
methyl isobutyl ketone		0	0	
proprietary ingredients		0	0	
titanium dioxide		0.34	0	
pigment extenders		0.28	0	
additives		0	0	
toluene		0	0.12	
propyl acetate		0	0	
MPK		0	0	
methyl ethyl ketone		0	0.12	
electricity		0	0	
natural gas		0	0	
steam		0	0	
:				
Air Emissions				
SOx		0.13	0.0039	
:				
:				

Table 3.8 Option Inventory			
		Option 2	**Option 3**
Functional Unit (FU)	ft^2	1000	
LCI Components	**Units**	**Quantity**	**Quantity**
Resource and Energy Consumption			
Electricity	BTU/FU	605433.01	555534.63
Natural gas	BTU/FU	10464119.78	9296247.95
Steam	BTU/FU	462896.19	425150.96
Water	lb/FU	31785.09	46271.34
Fuel	lb/FU	28242.48	29269.17
Crude oil	lb/FU	2007.55	1778.95
Bauxite	lb/FU	83.96	83.96
:			
:			
Air Emissions			
CO2	lb/FU	218.99	197.62
SOx	lb/FU	20.99	20.71
VOC	lb/FU	10.89	10.08
PM	lb/FU	4.42	4.39
NOx	lb/FU	4.42	4.26
Hydrocarbons	lb/FU	2.42	2.15
CO	lb/FU	1.01	0.58
Chlorine	lb/FU	0.42	0.42
MIAK	lb/FU	0.29	0.29
Isobutyraldehyde	lb/FU	0.26	0.26
:			
:			

Wastewater Emissions			
Wastewater	lb/FU	2432.41	2137.95
WW Reinj'd	lb/FU	117.92	104.49
WW Discharg.	lb/FU	52.15	46.21
Mobile ions	lb/FU	25.44	22.54
WW Injected	lb/FU	17.10	15.15
Sodium	lb/FU	10.51	9.31
Chloride	lb/FU	8.30	7.35
Oil and Grease	lb/FU	0.26	0.23
Titanium dioxide	lb/FU	0.09	0.15
:			
:			
Solid Wastes			
Hazardous Wastes	lb/FU	80.16	79.19
Solid Wastes	lb/FU	52.65	52.52
U238	lb/FU	3.92E-09	3.59E-09
Fly Ash	lb/FU	1.48E-09	1.36E-09
FGD Solids	lb/FU	5.71E-10	5.24E-10
Bottom Ash	lb/FU	4.14E-10	3.80E-10
Slag	lb/FU	1.58E-10	1.45E-10
:			
:			

Alternatively, the team may wish to use the issues identified in the screening stage to compare the impact potentials of the available options. If the intent of the life cycle engineering effort is more broadly to improve the overall environmental performance or to address general environmental issue areas, then the options characterization profile, possibly in conjunction with the option inventory, may be the more effective technique for the detailed analysis. Table 3.9 shows the characterization profile for the CARC System Options 2 and 3.

Table 3.9 Life Cycle Assessment Characterization Profile for the CARC System Options 2 and 3				
Environmental Requirement or Goal	**Impact**		**Option 2**	**Option 3**
		Contributory Materials	***Impact Potential***	***Impact Potential***
EF1. Reduced generation of waste solvents and paints	Human health – inhalation toxicity	**Aggregated Score:**	**13.205**	**11.004**
		ACETALDEHYDE	0.493	0.234
		ALUMINUM	0	9.336E-05
		BUTYL ACETATE (n-)	0.674	0
		BUTANOL	0.017	0.021
		CARBON TETRACHLORIDE	0.014	0
		CHLORINE	9.180	9.324
		CHLOROFORM	0.002	0
		CUMENE	0.026	0.022
		ETHYL BENZENE	0.005	0.010
		ETHYLENE DICHLORIDE	0.041	0
		FLUORINE	0.296	0
		HYDROCHLORIC ACID	0.014	0.021
		HYDROGEN CYANIDE	0.146	0.147
		ISOBUTYRALDEHYDE	0.478	0.478
		METHYL ETHYL KETONE	0.055	0.022
		METHYL ISOAMYL KETONE	1.151	0.205
		METHYL ISOBUTYL KETONE	0.033	0
		NITRIC ACID	0	0.000
		NITROPROPANE	0	0.006
		PHENOL	0.349	0.333
		TOLUENE	0.201	0.180
		TRICHLOROETHANE	0.009	0
		VINYL CHLORIDE	0.019	0

		XYLENE	0.067	0.065
	Aquatic fauna illness or death	**Aggregated Score:**	**0.670**	**2.024**
		CHLORINE	0.6362	1.9686
		COPPER COMPOUNDS	0.0009	0.0015
		LEAD	0.0320	0.0524
		ZINC	0.0006	0.0010
EF2. Reduced energy consumption	Fuel resources depletion	**Aggregated Score:**	**9789.524**	**8678.207**
		COAL	0.632	0.000
		NATURAL GAS	1758.676	1562.395
		PETROLEUM (CRUDE OIL)	8030.216	7115.812
EL1. Reduced VOC emissions	Smog formation	**Aggregated Score:**	**0.276**	**0.139**
		ACETALDEHYDE	0.0349	0.0166
		AROMATIC HYDROCARBONS (C8-C10)	0.0092	0.0151
		BUTYL ACETATE (n-)	0.0257	0
		BUTYL ALCOHOL	0.0035	0.0043
		CHLOROFORM	2.027E-05	0
		ETHYL BENZENE	0.0009	0.0019
		ETHYLENE	0.0021	0.0004
		METHANOL	0	1.683E-06
		METHYL ETHYL KETONE	0.0187	0.0076
		METHYL ISOAMYL KETONE	0.0938	0.0167
		METHYL ISOBUTYL KETONE	0.0047	0
		TOLUENE	0.0553	0.0498
		TRICHLOROETHANE	3.472E-05	0
		XYLENE	0.0272	0.0263
EL2. Reduced solvent and pigment discharges to sewer	Aquatic species illness or death	See EF1.		

EL3. Reduced solvent and metal-bearing pigment releases to land	Human health – inhalation toxicity	See EF1.		
	Aquatic species illness or death	See EF1.		
	Terrestrial species illness or death	**Aggregated Score:**	**1.746**	**1.074**
		ACETALDEHYDE	0.216	0.103
		ACETONITRILE	0.000	0.002
		BUTYL ALCOHOL	0.110	0.134
		CARBON TETRACHLORIDE	0.003	0.000
		CHLOROFORM	0.006	0.000
		COPPER COMPOUNDS	0.000	0.001
		CUMENE	0.052	0.044
		DICHLORODIFLUOROMETHANE	0.000	0.001
		HYDROCHLORIC ACID	0.005	0.008
		HYDROGEN CYANIDE	0.146	0.147
		ISOBUTYRALDEHYDE	0.478	0.478
		METHYL ETHYL KETONE	0.074	0.030
		METHYL ISOAMYL KETONE	0.590	0.105
		METHYL ISOBUTYL KETONE	0.040	0.000
		NITRIC ACID	0.000	0.005
		VINYL CHLORIDE	0.008	0.000
		XYLENE	0.017	0.016
EL4. Decreased solid waste generation	Habitat loss/land use	**Aggregated Score:**	**239.297**	**237.170**
		HAZARDOUS WASTE	160.33	158.39
		SOLID WASTE	78.97	78.78
ER1. Reduced particulate releases	Human health – inhalation toxicity	See EF1.		

	Terrestrial species illness or death	See EL3.		
EG1. Reduced fuels and resource consumption	Resource depletion	**Aggregated Score:**	**10233.633**	**9105.511**
		BAUXITE	335.857	335.857
		CHROME OXIDE	6.575	6.575
		COAL	0.632	0.000
		COBALT OXIDE	2.173	2.173
		IRON ORE	2.776	2.905
		LIMESTONE	4.653	4.653
		MAGNESIUM ORE	1.624	1.624
		NATURAL GAS	1758.676	1562.395
		PETROLEUM (CRUDE OIL)	8030.216	7115.812
		PHOSPHATE ROCK	4.532	0.000
		SALT (SODIUM CHLORIDE)	31.106	31.384
		SILICA	9.861	9.658
		SODA ASH	2.624	2.624
		TITANIUM	18.220	29.851
		URANIUM (235, 236, 238)	0.000	0.000
		ZINC	24.108	0.000
	Acid precipitation	**Aggregated Score:**	**24.080**	**20.714**
		AMMONIA	0	0
		HYDROCHLORIC ACID	0.00084	0.00123
		NOX	3.093	0
		SOX	20.986	20.713
	Climate change	**Aggregated Score:**	**221.802**	**207.522**
		CARBON TETRACHLORIDE	2.645	4.258
		CO2	218.992	197.618
		DICHLORODIFLUOROMETHANE	0	5.646
		TRICHLOROETHANE	0.165	0

Based on the aggregate impact potential scores, Option 3 appears to be the environmentally preferred system when developing specifications for a replacement CARC maintenance procedure. With the exception of aquatic toxicity impact potential, the combination of alternative primer and alternative spray gun technologies affords the best environmental performance relative to the option of the alternative gun alone. However, relative to the current practice both options represent reductions in impact potential for all nine impact issue areas.

3.3.4 Specification Development

Information developed by the evaluation team on the environmental, cost, and performance aspects of alternative CARC system options has indicated that a technical order modification involving the substitution of the water thinable primer and the turbine HVLP should be prepared. However, in order to implement the change in specifications, there may be several additional issues to be dealt with. These issues include a lack of demonstrated experience with the technologies in actual production settings, considerations relating to procurement practices, and incremental training of operators in the use and proper disposal of these new materials and application technologies.

Performance demonstration refers to the actual painting of vehicles using the alternative system. Although the conditions established during the life cycle engineering effort should be sufficient to modify the specifications and ensure a reasonable level of confidence in the new technologies, it will likely be necessary to further demonstrate their effectiveness over a broader range of environmental and vehicle surface conditions.

Procurement considerations include two aspects – conditions relating to justification of capital items acquisition, particularly as related to items that are more expensive than the original equipment, and better understanding of who must approve of the purchase of alternative materials. Based on preliminary information, the acceptance of alternative materials should require no approvals beyond that of the item managers. This should be a formality once the performance verification is completed.

Each environmental requirement or goal, together with the associated indicator or indicators, is listed, along with the impact scores for the contributing materials to each impact category. The methodology for deriving the impact score values from the inventory data is described in detail in the CARC LCA report (EPA, 1996). The team can identify which option provides the best mix of characteristics in one of two ways – by inspection of the individual material contributions or by comparison of the aggregated scores within each impact indicatory category. Because the methodology used to generate the scores provides a consistent set of impact units, the aggregate score is simply the arithmetic sum of the individual contributions. Note that combining impact potentials across issues is not permissible. Unless a formal approach to specifying the relative importance of the issue areas is employed, the team will simply apply its judgement to arrive at a decision. One such formal method is presented in the CARC LCA report (EPA, 1996). Others are discussed in the LCA literature (SETAC, 1997; Baumann, 1995, and SETAC-Europe, 1994).

Incremental training requirements are expected to be minimal. Nevertheless, safety and related procedural considerations should be included in the guidance for the alternative spray gun. Any changes in the application techniques or recoating times for the alternative materials should be included in the revised technical orders. Additional recommendations on proper handling and disposal should also be part of the application and use specification.

4. Upgrades

This section describes the consideration of life-cycle environmental factors when introducing incremental and routine improvements in the performance of existing products, systems, processes, or facilities[3].

4.1 Products and Systems

Product and system upgrades are often introduced when an item currently being sold or already placed in service is not performing at a desired level or when it is felt that a greater market share may be achievable with a better performing product. Customer feedback through the maintenance, technical support, marketing, or customer service channels may trigger a need to modify components, to re-engineer certain assemblies for better service or replacement access, or a myriad of other performance considerations. A desire to improve the manufacturability of a product or system may also create an opportunity for upgrades. Under most circumstances the environmental performance of the product or system will not be the primary reason for undertaking an engineering effort to upgrade. Nevertheless, life cycle engineering offers the potential for consideration of possible improvements in the environmental aspects of a product or system at the same time that performance- or cost-drivers are creating a need to improve its technical or cost envelope.

4.2 Processes and Facilities

Process and facility upgrades may be either consequential to a product or system upgrade or independent. Oftentimes, changing requirements for production of the components or assemblies comprising a product will initiate an assessment of the operational efficiency, throughput rates, or manufacturing quality procedures. In turn, once the evaluation team has a charter to modify the process or facility, life cycle engineering can be employed to ensure that environmental aspects are considered along with productivity and cost. More than this, the LCE framework encourages the team to select processes and facility upgrade elements that avoid the transfer of impacts to supplier organizations.

Even in the absence of product-driven initiatives to upgrade, process and facility improvements can be justified on the basis of improved life cycle costs for the operations, improved quality of products, debottlenecking of production, or other non-environmental considerations. However, with regard to processes and facilities upgrades, environmental factors can be an important driver apart from production costs. Life cycle engineering offers the capability for an evaluation team to simultaneously consider process changes that reduce environmental compliance costs, reduce overall facility environmental burdens, and beneficially impact productivity and profitability.

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[3] When upgrading is non-routine and significant, rather than incremental, the decision falls in the "New" type.

4.3 LCE Case Study: Photovoltaic Module Development

Photovoltaic modules (PV) are devices that convert solar energy into electricity. The UPM-880 tandem junction power generation module, a PV produced by United Solar, uses thin film amorphous silicon as the photovoltaic material and contains two identical semiconductor junctions. The UPM-880 is 119.4X34.3X3.8 centimeters in size and weighs 3.6 kilograms.

4.3.1 Targeting the Evaluation

Establishing the Function being Provided

The function of the UPM –880 is to convert sunlight to energy. It has a rated output power of 22 watts, which represents a stabilized conversion efficiency of 5%. The UPM-880 has a 10-year warranty.

Naming an Evaluation Team

The evaluation team for this effort consisted of management and technical functions. Members of the team included:

- National Pollution Prevention Center staff who are experts in Life Cycle Design,
- A Vice President of Research and Technology at United Solar, and
- A Senior Research Scientist at United Solar.

These groups interacted on a number of occasions. The Research scientist was responsible for data collection and analysis of energy module manufacturing. The Vice President of Research and Technology helped to initiate and define the scope of the project.

Developing Requirements and Goals

The requirement of the design activity was to guide the next generation design of the UPM-880 by improving upon four metrics:

- **Energy payback time-** the length of time required for a module to generate energy equal to the amount required to produce it from raw materials.
- **Electricity production efficiency-** the ratio of the total energy produced by a generating system over its lifetime to the sum of energy inputs required for the system's manufacture, operation and maintenance (including fuel), and end-of-life management to the amount of radiant energy as sunlight incident on the generating system over its lifetime. The metric can be used to compare all types of renewable fossil fuel-based generating technologies.
- **Life cycle conversion efficiency** – the ratio of the energy produced over a generating system's lifetime minus energy inputs required for the system's manufacture, operation and maintenance (including fuel), and end-of-life management to the amount of radiant energy as sunlight incident on the generating system over its lifetime. This metric is most useful for comparing solar-fueled generating systems to each other, as opposed to fossil fuel systems.
- **Life cycle cost** – the total acquisition, operation and maintenance, and retirement costs for a generating system divided by the total amount of energy generated over its lifetime. The metric can be used to compare all electricity generating systems.

Table 4.1 provides an assessment of requirements and goals based on these metrics. Production efficiency and life cycle cost were considered as requirements.

Table 4.1 UPM-880 Assessment Requirements and Goals

Category	Applicable Life Cycle Stage				Requirements and Goals	Requirement (R) or Goal (G)
	MP	MC	USM	D		
Performance						
Electrical	X	X	X	X	Decrease payback time.	G
Electrical					Increase production efficiency	R
Electrical		X	X	X	Increase life cycle conversion efficiency.	G
Cost						
Equipment, and installation		X	X		Reduce cost.	R
End-of-Life Management				X	Reduce life cycle cost	G

Proposing Engineering Technologies and Options

Design strategies were found to depend on many factors such as useful life of the module, opportunities for reusing modules in less demanding applications, and efficiencies associated with improved technology at the time of retirement. PV technology development focuses on increasing conversion efficiency and reducing costs. Electricity production efficiency, energy payback time, and life cycle cost add valuable new perspectives in guiding technology development. These metrics illuminate material and process choices, and help utility companies, policymakers, and the public make accurate comparisons between technologies.

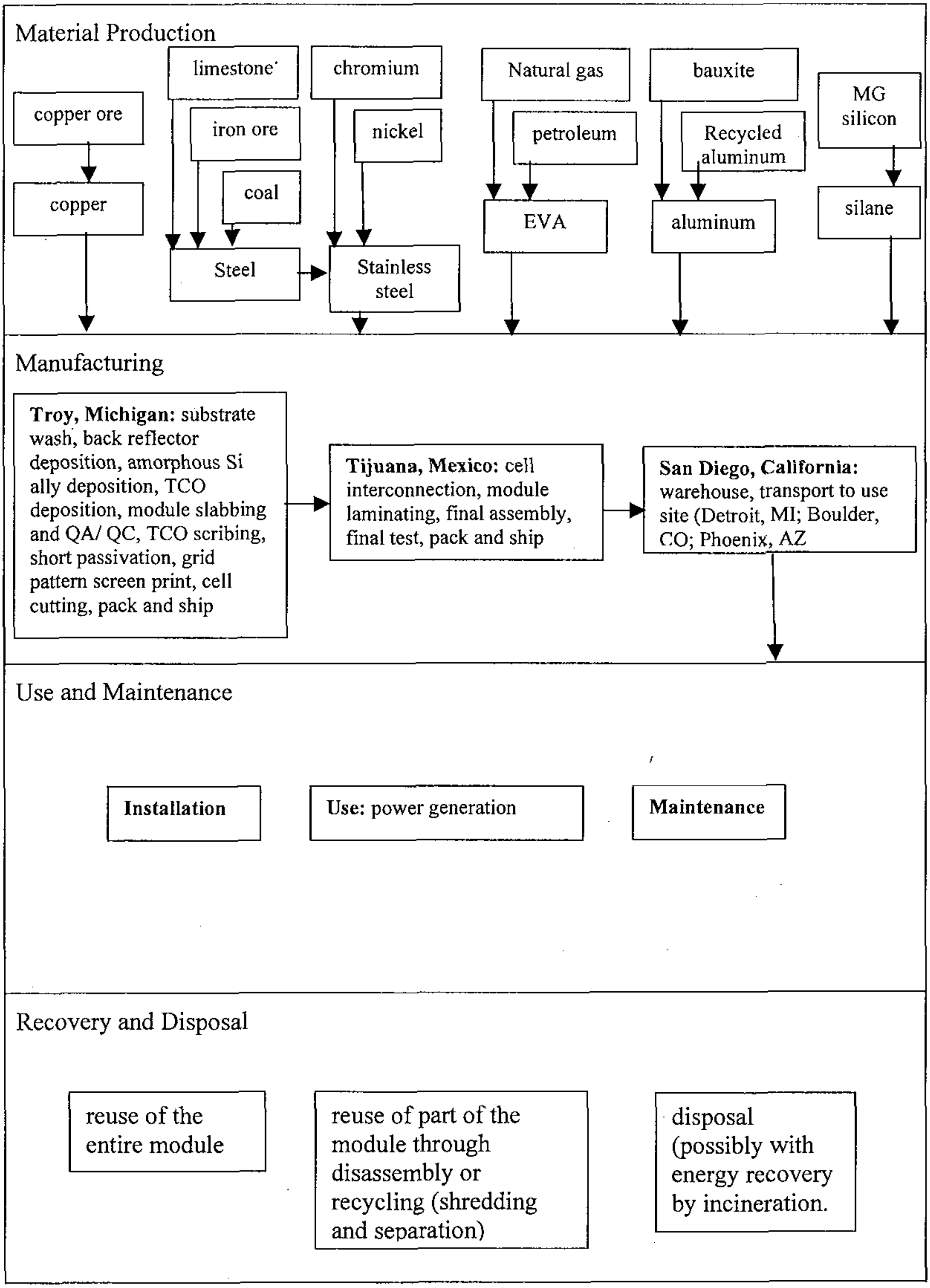
Design strategies for end-of-life management phase were explored. The analysis was conducted for standard and frameless versions of the UPM-880 module.

4.3.2 Preliminary Assessment

Defining the Technology Life Cycles

Over 26 materials are used in the production of the UPM-880, 20 of which are actually incorporated into the finished product. Several processes used for cleaning, etching, and short passivation are not incorporated into the module, although they were included in the analysis of embodied energy. Incorporated materials include gases, liquids, and solids, both metals and plastics. The consituents products were listed and sorted by mass to highlight their continued attension in the assessment. The highest contribution to the mass was the anodized aluminum extruded frame (38%), the EVA encapsulation (25%), the galvanized mild steel backing plate (25%), and the stainless steel substrate (11%).

Figure 4.1 Defining the Technology Life Cycle



The phases of the product investigated included material production, manufacturing, use, and end-of-life management. As shown in Figure 4.1, it was beyond the scope to examine raw material extraction and processing operations in depth for all materials used in the production of the UPM-880. The manufacturing phase is composed of a large number of components that are carried out in the United States and Mexico. The use phase of a UPM-880 module has installation, use (power generation), and maintenance. Because there are limited documented examples of what happens to PV modules at the end-of-life, the end-of-life management phase was addressed in terms of three possible scenarios: (1) reuse of the entire module, (2) reuse of part of the module through disassembly or recycling (shredding and separation), or (3) disposal (possibly with energy recovery by incineration.

Upon examination, the team found the aluminum frame an obvious candidate for reuse.

4.3.2 Preliminary and Detailed Assessments

The preliminary and detailed assessments were combined to include the quantification of the set of metrics linked to the requirements and goals. Material energy requirements were calculated for each of eight components of UPM-880. For each component a low case and a high case energy requirement were developed. The totals for the high and low cases were 831.4 MJ and 25.5 MJ, respectively. The energy requirements for the nine major steps of manufacturing were also calculated as equivalent primary energy. These data were collected by measuring electrical consumption of each machine for the amount of time necessary to process one module of UPM-880. The total energy requirement was 201.2 MJ.

Conversion efficiency metrics were calculated for three locations: Detroit, MI; Boulder, CO; and Phoenix, AZ. Energy payback time in years was calculated as module production energy (in kWh) divided by energy generated per year. These calculations were made for conversion efficiency factors ranging from 5% to 9%. The calculated payback periods for the three locations and five different conversion factors ranged from 1.3 to 13.4 years. Energy production efficiency was calculated summing the energy produced by a generating system over its life time, and dividing it by the sum of the energy inputs required to manufacture and transport, install, operate and maintain, and disposal or reclaiming of the system at the end of its life time. Conversion efficiency was defined and calculated as energy produced over a generating system's lifetime minus energy inputs required to manufacture and transport, install, operate and maintain, and dispose or reclaim that system divided by the amount of radiant energy as sunlight incident on the generating system over its lifetime. Electricity production efficiency and conversion efficiency metrics were calculated for 10, 15, 25, and 25 year assumed lifetime.

A life cycle cost analysis was conducted to estimate the total cost of electricity production from the UPM-880 module. Initial purchase price, installation, maintenance, and retirement costs were included in this analysis. The estimates were made for 10, 15, 20, and 25 year lifetimes for the same three geographic locations that were cited earlier. These estimates ranged from $0.24 per kWh to $1.23 per kWh.

4.3.4 Specification Development

Two components of the UPM-880 were illustrated as major opportunities for design improvement: the aluminum frame and the EVA encapsulant. The energy invested in the aluminum frame consists of material production energy and energy required to extrude and anodize the frame parts. Material production energy can be reduced by using a higher proportion of secondary material or by using a different, less energy intense material. Also, the aluminum frame is a good candidate for reuse.

The useful life was recognized as a primary design parameter. Early design failures illustrated that moisture intrusion is a sure cause of module failure. EVA encapsulant, which is not completely impermeable to moisture, has been a factor in the determination of useful life. EVA also requires high energy for lamination.

5. New Design

This section describes the consideration of life-cycle environmental factors in the development, and testing of original/first-time products, systems, processes, or facilities. A chemical manufacturing case study example is included to illustrate how the elements of the life cycle engineering framework apply to these types of decisions.

5.1 Products and Systems

New products and systems have one characteristic that distinguishes them from upgrades or maintenance – degree of evaluation team knowledge of the product or system attributes. Whereas most upgrades or maintenance procedure decisions involve an assessment of how commercial technologies will best be suited for improving existing products and system, knowledge of the environmental, cost, and performance characteristics of new products and systems will be by definition limited. New products and systems are by nature subject to greater uncertainty in their life cycle engineering characterization. This higher degree of uncertainty needs to be acknowledged and accounted for by the evaluation team.

5.2 Processes and Facilities

The development of new processes shares much of the uncertainties associated with new products and systems development. The lack of a full understanding of the performance, cost, and environmental characteristics means that the team will need to return to the analysis periodically and reevaluate their conclusions as data about the process become better known. One way to address this uncertainty would be to delay completion of the detailed step of the assessment until later in the development process realizing that the flexibility to modify the process may be more constrained. New facility development has fewer uncertainties associated with the physical structure since even in the case of novel features, such as lighting, power, and space conditioning, much of the technology will be choosing among commercialized options. However, new facilities development also brings in elements associated with environmental assessment of siting alternatives and the related issue of due diligence in assuring environmental sensitivity of the site development process.

5.3 LCE Case Study: BDO Process Development

1,4-Butanediol (BDO) is a widely used chemical building block for numerous commercial chemical and polymeric compounds. Conventional processes for the synthesis of BDO use petrochemical feedstocks for their starting materials. About 90% of 1995 domestic production used the Reppe process in which acetylene and formaldehyde are reacted to produce 1,4-butenediol. This intermediate is then hydrogenated to produce BDO. An alternative process was sought to produce BDO via a route not dependent on traditional feedstocks.

5.3.1 Targeting the Evaluation

Establishing the Function being Provided

The function of the new process is to produce a unit quantity of BDO using non-conventional feedstocks at a cost below the current production cost of BDO produced by conventional synthesis routes. Note that the functional specifications for the process do not dictate a purity level for the produced BDO. Rather, the downstream use of the material will determine how much impurity is tolerable and how the primary manufacturing process needs to accommodate the required purity levels.

Naming an Evaluation Team

The evaluation team for this effort consisted of several distinct groups. Members of the team included:

- U.S. Department of Energy, Alternative Feedstocks Program staff who oversaw the development team and provided an integration perspective on balancing of environmental versus other goals.
- Environmental specialists whose responsibility was to identify the characteristics of the conventional BDO manufacturing system that had the potential to create adverse environmental impacts and to analyze the impact potential profile of an alternative process.
- Process chemistry and engineering developers who were involved in laboratory and pilot scale process design experiments against a set of well-defined criteria.
- Process cost analysts who were responsible for estimating the costs of the operations involved in the alternative process.
- Life cycle process engineers who were responsible for establishing the system boundaries, identifying and collecting process information on the upstream materials production, and characterizing the waste management aspects of the coatings operation. This group also had the task of making recommendations back to the process engineering team to incorporate improvements into the next generation design.

These groups interacted on a number of occasions, but could not function as an entirely integrated team. The latter four groups formed the primary LCE team.

Developing Requirements and Goals

Initial requirements for the new process consisted of a combination of performance, cost, and renewable feedstock attributes. Details on these requirements (R) and goals (G) may be found in Table 5.1, which is an excerpt of *Routine and Unanticipated Maintenance Worksheet 1*. The initial set of aspects were largely confined to the manufacturing life cycle stage, although parameters such as feedstock cost and availability are associated the upstream stages as well as the in-house activities. These initial requirements were not developed with a life cycle engineering framework in place.

Table 5.1 New BDO Process Requirements and Goals

Category	Applicable Life Cycle Stage: MP	MC	USM	D	Requirements and Goals	Requirement (R) or Goal (G)
Performance						
Chemical			X		Fermentation step yields must meet targets for purification stage	R
Chemical			X		Acceptable product quality as defined by purchaser specifications	R
Cost						
Materials			X		Lower cost for feedstock and process chemicals	R
Materials and Equipment			X		Production cost substantially below current estimated cost	R
Materials			X		Reduced labor costs compared with baseline	G
Environmental – Facility						
Hazmat management and waste			X	X	Reduce or eliminate generation of waste solvents and sludges	G
Energy consumption	X	X	X		Less than baseline	R
Environmental – Local						
Photochemical smog production	X	X	X		Reduce emissions compared with conventional process	R
Water pollution			X		Minimize solvent and nutrient discharges to surface or groundwater	G
Toxic materials in the environment	X	X	X	X	Minimize solvent and biosolids releases	R
Landfill space		X	X	X	Decrease solid waste generation	G
Environmental – Regional						
Visibility impairment			X		Reduce the amount of particulates released	G
Environmental- Global						
Resource conservation	X	X	X	X	Reduce fuels consumption and use renewable resources	R

Proposing Engineering Technologies and Options

During the course of developing the process flowsheet that was ultimately used for the environmental assessment, the engineering team assessed and modified the technologies for synthesizing and purifying the product of the alternative synthesis route several times. These technology options included alternative fermentation reactor configurations, several sets of purification process steps and multiple options for co-product and waste processing prior to recycling or disposal. In all instances these options were rejected on the grounds that they failed to meet the performance and cost targets and therefore any environmental requirement or goal assessment was moot. However, in an ideal deployment of the LCE approach, those initial options would have at least had some preliminary assessment for their environmental attributes to complement the performance and cost analyses.

5.3.2 Preliminary Assessment

Defining the Technology Life Cycles

Figure 5.1a through c shows the life cycle activities and material/energy flows associated with each of the technologies. This analysis boundary is similar to that shown previously for the CARC example. In this case the downstream boundary for the new process analysis is the manufacturing of a unit quantity of BDO. Because the requirements included a statement that the purity be acceptable for the intended use (implying that the alternative process cannot produce inferior product relative to that derived from the conventional technology), the analysis can be streamlined through exclusion of the stages involving the use and disposition of the product. Also, because the criteria span more than the process operation and maintenance life cycle stage, the LCE framework requires the description and consideration of the whole process life cycle.

Figure 5.1a BDO Technology 1: Glucose Fermentation to Succinic Acid

Technology	Technology 1: Glucose Fermentation to Succinic Acid (SA)
Additional material and equipment requirements	• Minor nutrients (HCl, Tryptophan, Cysteine) and process control chemicals (NaOH and CO_2) • Dewatering and biosolids recovery and pre-processing (dewatering) equipment • Fermentation reactor and associated feed and control systems
Operational and maintenance procedures	In accordance with manufacturer's literature and product recipe.

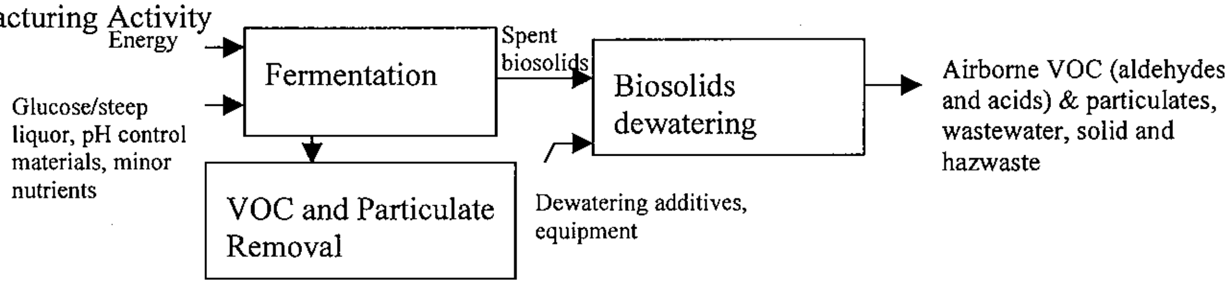
Material Production

Succinic acid is produced through the mediation of bio-engineered microbes. The reactor feed consists of corn-derived glucose and corn steep liquor along with certain micro-nutrients required for the continued viability of the biomass. In addition to the carbon source production steps, material production activities for process control chemicals are included. Excluded are the upstream materials production operations for minor nutrients since these comprise only 2.3% of the total input mass.

Technology Manufacturing

In keeping with typical LCA practice and the streamlined nature of this assessment, the environmental aspects of manufacture of the fermenter and related equipment were not included.

Manufacturing Activity



Material Recovery and Disposal

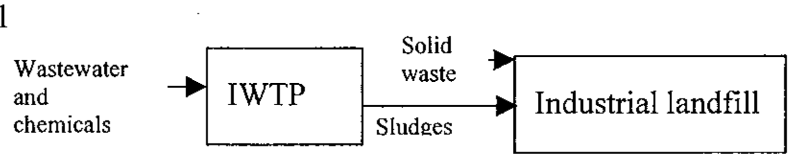


Figure 5.1b BDO Technology 2: Succinic Acid Purification (Electrodialysis)

Technology	Technology 2: Succinic Acid Purification
Additional material and equipment requirements	• Electrolytes and process control chemicals • Coproduct recovery equipment • Electrodialysis cell and associated feed and control systems
Operational and maintenance procedures	In accordance with manufacturer's literature and product recipe.

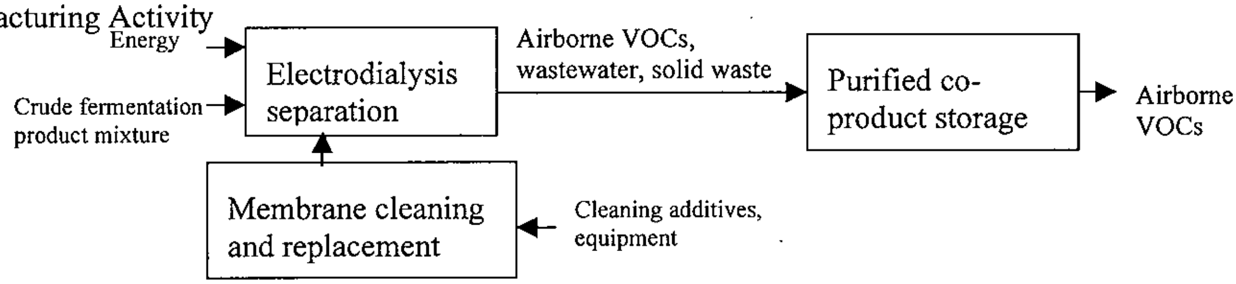
Material Production

Succinic acid produced in the previous step is not pure. It is a co-product along with several other compounds that need to be separated in order for the SA material to be useable for BDO production. One technology for effecting this separation is electrodialysis in which a mixture of materials are placed in a chamber with a semi-permeable membrane forming one of the interior surfaces. Application of an electric field forces certain components of the liquid through the membrane where they are concentrated relative to the original solution. Excluded are the upstream materials production operations for some of the membrane maintenance chemicals since these comprise a small percentage of the total input mass.

Technology Manufacturing

In keeping with typical LCA practice and the streamlined nature of this assessment, the environmental aspects of manufacture of the electrodialysis cell and the membranes were not included.

Manufacturing Activity



Material Recovery and Disposal

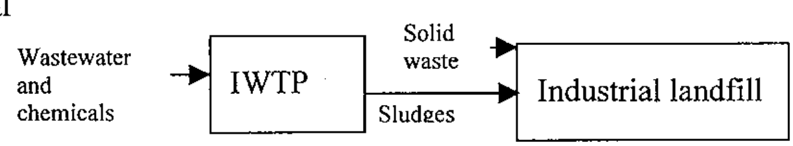


Figure 5.1c BDO Technology 3: Catalytic SA Reduction to BDO

Technology	Technology 3: Catalytic SA Reduction to BDO
Additional material and equipment requirements	• Catalyst • Hydrogen • Reactor and associated equipment
Operational and maintenance procedures	In accordance with manufacturer's literature and product recipe.

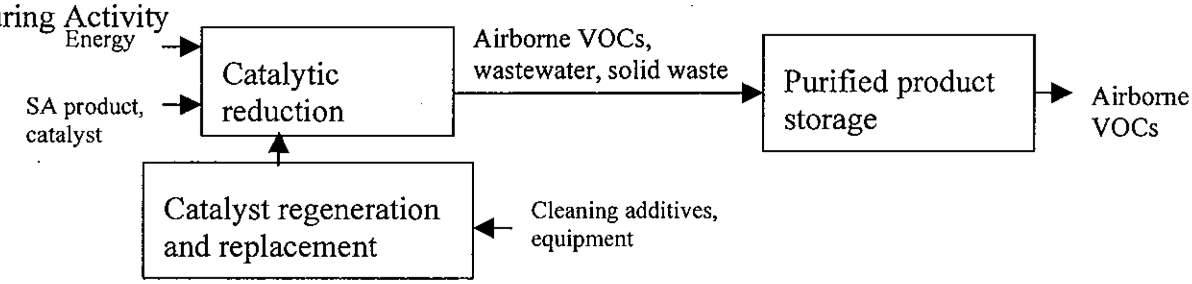
Material Production

The production of hydrogen was included as part of the upstream stages associated with wet milling of corn. Because hydrogenation of oils forms a basic part of the corn processing for many products, it was recommended that the evaluation team not create a stand-alone hydrogenation step as part of the BDO facility. Upstream production of the components of the aluminum oxide catalyst was included.

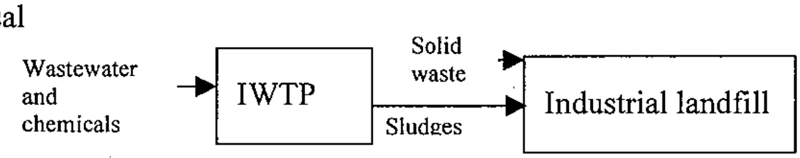
Technology Manufacturing

In keeping with typical LCA practice and the streamlined nature of this assessment, the environmental aspects of manufacture of the reactor and the associated equipment were not included.

Manufacturing Activity



Material Recovery And Disposal



In this evaluation the choice of technologies was pre-positioned to effect the best current economics of BDO production while satisfying the criterion of using an alternative (non-fossil) feedstock. Therefore, alternative technologies were not identified and a series of preliminary assessments of the degree of achievement of requirements and goals was not prepared, as was the case for CARC. (see Section 3.3.2).

5.3.3 Detailed Assessment

Retargeting the Assessment

The detailed assessment stage consisted of cost and environmental aspects. Performance characteristics were addressed by requiring the product BDO to meet purity levels for use in downstream stages and by the impacts on the production costs of additional separation and purification steps. The economic analyses were based on costs in then current year dollars for firm fixed contract materials procurement from commercial sources. The analysis assumed co-location of the BDO facility at a corn wet mill where the glucose feedstock could be provided with no additional off-site transportation costs. The LCA was based on a functional unit produced at a hypothetical location in the Midwest (Iowa or Illinois).

Environmental requirements and goals were analyzed using a Life Cycle Impact Assessment directed at resource and energy consumption, environmental burdens and waste generation. The environmental evaluation of the selected options consisted of performing a life cycle assessment (LCA) on the technologies outlined above that comprise the alternative production sequence flowsheet in comparison with those associated with the conventional BDO production using the Reppe process. Each analysis consisted of a life cycle inventory to measure the energy and materials flows for the production of selected precursors and BDO. The manufacturing of the capital equipment was not included in this analysis in keeping with standard LCA practice. The downstream boundary was purified BDO ready to ship to customers. Although technology-specific data were available for each of the three steps in the alternative process based on detailed flowsheet modeling using a commercial simulation package, the LCI data were aggregated so as not to disclose certain proprietary pieces of information about the alternative technologies.

Within the primary manufacturing portions of the bio-based BDO life cycle, the data in Table 5.2 indicate that the burden contributions from separation and purification of the crude succinic acid product are significant. In addition, if power is purchased from off-site generation, the contribution to the life cycle profile from electric power generation is dominant. When the overall impacts of the two technologies are compared (Tables 5.3 and 5.4), the intuitive sense that the system based on renewable crop resources is environmentally preferable is seen to be incorrect. The conventional system based on natural gas is the preferred system for 9 of the impact categories. At least in its original design configuration the corn-based system is preferable only on the aspects of resource depletion and carcinogenicity.

LCE results of this type for new systems are appropriately used to develop more refined designs. Based on the analysis of the contributing operations, a number of modifications can be identified (Figure 5.2). For the agricultural portions of the life cycle, use of conservation tillage to reduce soil losses and increase carbon retention will improve the global warming and eutrophication impact scores. Recycling of the fermentation media back to the farm also will improve productivity and may reduce the need for fertilizers slightly. Within the BDO production operations, three improvements were identified. Use of hydrogen produced at the corn wet mill will avoid the cost and environmental burdens associated with building and operating a separate hydrogen plant. Incremental improvements in the electrodialysis system will reduce power consumption and the associated emissions as well as provide a higher purity (and therefore less waste generating) feedstock for the BDO production step.

In addition to improving the environmental profile of the system the LCE analysis identified the potential to better integrate the BDO plant into the surrounding agricultural production activities. Finally, the changes will save a couple of pennies per pound in production costs. This may not seem like very much but, at the projected production scale of 100 million pounds per year, the annual savings amount to more than 2 million dollars.

Figure 5.2 Design Improvements Identified through LCE Process

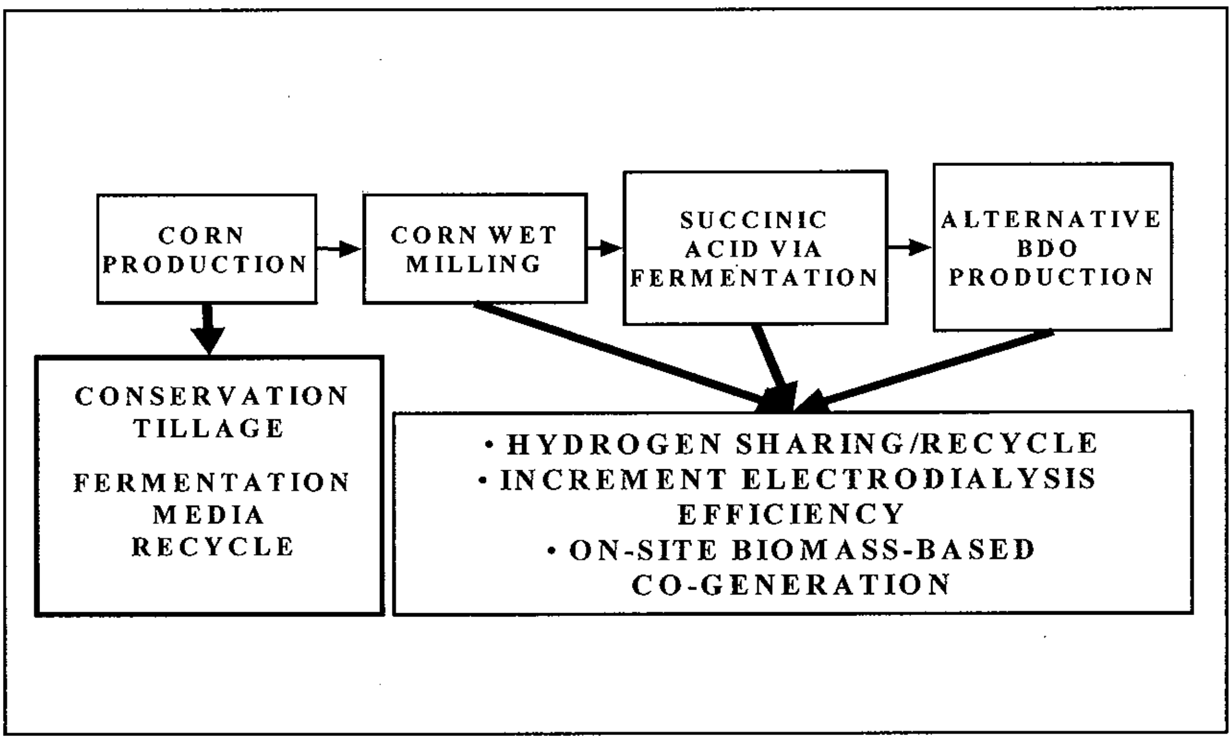


Table 5.2

Production of 1,4-Butanediol
Summary LCI

	Emissions and Consumption (lb/lb BDO)									
	Conventional Process					Alternative Process				
	Trunk		BDO			Trunk		BDO		
Component	**Processes**	**Energy**	**Process**	**Energy**	**Total**	**Processes**	**Energy**	**Process**	**Energy**	**Total**
Air Emissions										
Nox	1.93E-04	5.85E-04		7.11E-03	7.89E-03	3.60E-04	3.92E-03	0	1.47E-02	1.90E-02
PM-10		3.82E-06		5.80E-05	6.18E-05	1.11E-02	1.01E-03	0	1.80E-03	1.39E-02
CO	7.60E-05	1.31E-04	2.17E-03	8.92E-04	3.27E-03	3.61E-04	6.13E-03	5.34E-03	5.10E-03	1.69E-02
CO2	2.59E-02	0.11	0.34	2.82	3.29	0.06	0.84	-0.74	3.13	3.30
Organic Compounds			1.29E-03		1.29E-03	1.85E-04	1.61E-06	3.16E-03		3.35E-03
Non-Methane VOC's		1.79E-06		2.85E-05	3.03E-05	7.33E-04	8.45E-06	0	4.66E-05	7.88E-04
Methane	2.43E-05			3.39E-05	5.82E-05	0	6.65E-06	0	8.27E-06	1.49E-05
N2O					0	4.84E-04	4.21E-04	0	7.29E-04	1.63E-03
MEA			1.38E-05		0			3.38E-05		3.38E-05
Total Particulate	7.75E-06	6.53E-05		1.47E-04	2.20E-04	9.29E-03	1.53E-03		1.35E-03	1.22E-02
HCL					0	1.12E-05	0			1.12E-05
Ammonia	5.96E-06	1.58E-08		2.29E-08	6.00E-06	4.49E-04	2.66E-08		3.29E-07	4.49E-04
Chlorine					0.00E+00	1.23E-06	0	8.36E-07		2.06E-06
Sulfuric Acid	1.84E-09				1.84E-09	7.57E-07	0			7.57E-07
Sox	3.30E-06	1.08E-03	7.93E-06	1.57E-03	2.65E-03	4.62E-04	3.63E-03	1.95E-05	2.52E-02	2.93E-02

Hydrocarbons	2.93E-04	3.51E-05		5.08E-05	3.79E-04	1.34E-05	3.92E-04		7.29E-04	1.13E-03
Aldehydes	1.70E-06	1.58E-08		2.29E-08	1.74E-06	1.48E-05	2.13E-06		3.29E-07	1.72E-05
Organic Acids	2.17E-06				2.17E-06		1.34E-06			1.34E-06
NO					0	2.26E-03				2.26E-03
Nitric Acid					0	6.21E-06	0			6.21E-06
Fluoride					0	5.64E-07	0			5.64E-07
Acid Mist					0	3.18E-05	0			3.18E-05
Alachlor					0	3.17E-05				3.17E-05
Atrazine					0	5.85E-05				5.85E-05
Metalachlor					0	3.88E-05				3.88E-05
Cyanazine					0	3.03E-05				3.03E-05
Fonofos					0	4.69E-06				4.69E-06
Turbufos					0	1.24E-05				1.24E-05
Chlorpyrifos					0	8.07E-06				8.07E-06
Lead		2.10E-07		3.04E-07	5.14E-07		3.53E-07		4.36E-06	4.71E-06
Mercury					0			1.07E-07		1.07E-07
Acetylene			4.61E-05		4.61E-05					0
Kerosene		1.62E-07		2.35E-07	3.97E-07		2.73E-07		3.37E-06	3.64E-06
Formaldehyde	1.54E-05		5.70E-05		7.24E-05					0
Hydrogen			0.00E+00		0					0
Nitrogen			3.14E-02		3.14E-02					0
Copper	2.65E-08		2.26E-06		2.28E-06					0
Nickel	2.65E-08		1.11E-08		3.76E-08					0
Rhodium			0.00E+00		0					0
Butyl alcohol	1.38E-09		3.10E-05		3.10E-05					0

Propionaldehyde			6.54E-06		6.54E-06					0
Acetone	7.37E-07		2.69E-05		2.76E-05					0
Toluene			8.06E-05		8.06E-05					0
Methanol	5.81E-05				5.81E-05					0
Zinc	2.65E-08				2.65E-08					0
SO2	2.28E-05				2.28E-05					0
Hexane	5.87E-06				5.87E-06					0
Heptane	7.56E-06				7.56E-06					0
Octane	5.05E-06				5.05E-06					0
C-7 cycloparaffins	1.06E-06				1.06E-06					0
C-8 cycloparaffins	3.89E-07				3.89E-07					0
Pentane	3.66E-06				3.66E-06					0
Ethane	4.19E-06				4.19E-06					0
Propane	6.57E-06				6.57E-06					0
n-Butane	5.20E-06				5.20E-06					0
iso-Butane	2.59E-07				2.59E-07					0
Benzene	6.49E-08				6.49E-08					0
Wastewater Emissions										
Wastewater	5.79E-01		8.36E-01		1.42E+00	7.87E+00		3.07E+01		3.86E+01
BOD5		1.58E-08		2.29E-08	3.88E-08	6.29E-04	2.66E-08	1.04E-03	3.29E-07	1.67E-03
Total Suspended Solids		3.45E-08		4.98E-08	8.43E-08	7.86E-04	5.79E-08	1.50E-03	7.15E-07	2.29E-03
Phosphorus					0	1.23E-04				1.23E-04
Potassium					0	5.10E-04				5.10E-04
Sodium	1.27E-03				1.27E-03			1.10E-02		1.10E-02
Choride					0			1.98E-02		1.98E-02

Chlorine						5.04E-08			5.04E-08
Ammonia					0	8.81E-06			8.81E-06
Alachlor					0	2.77E-07			2.77E-07
Atrazine					0	3.00E-06			3.00E-06
Metalachlor					0	1.22E-06			1.22E-06
Cyanazine					0	1.69E-06			1.69E-06
Fonofos					0	8.09E-08			8.09E-08
Turbufos					0	2.14E-07			2.14E-07
Chlorpyrifos					0	2.31E-07			2.31E-07
Nitrates (as nitrogen)					0	1.94E-03			1.94E-03
Sulfuric Acid		1.02E-04		1.48E-04	2.50E-04		1.72E-04	2.12E-03	2.30E-03
Iron		3.20E-04		4.63E-04	7.84E-04		5.38E-04	6.65E-03	7.19E-03
Dissolved Solids	6.05E-08	1.68E-05		2.43E-05	4.12E-05		2.83E-05	3.49E-04	3.77E-04
COD		7.11E-08		1.03E-07	1.74E-07		1.19E-07	1.48E-06	1.59E-06
Phenol		5.29E-09		7.65E-09	1.29E-08		8.88E-09	1.10E-07	1.19E-07
Sulfide		5.29E-09		7.65E-09	1.29E-08		8.88E-09	1.10E-07	1.19E-07
Oil and Grease	3.13E-05	1.06E-08		1.53E-08	3.13E-05		1.78E-08	2.20E-07	2.37E-07
Acid		1.06E-08		1.53E-08	2.59E-08		1.78E-08	2.20E-07	2.37E-07
Metals		5.29E-09		7.65E-09	1.29E-08		8.88E-09	1.10E-07	1.19E-07
Formaldehyde			2.98E-05		2.98E-05				0
Acetylene			1.81E-05		1.81E-05				0
Copper	1.70E-09		1.34E-06		1.34E-06				0
Nickel	2.12E-09		7.70E-07		7.72E-07				0
Butyl alcohol			1.10E-05		1.10E-05				0
Zinc	3.03E-09				3.03E-09				0

Wastewater Reinjected	2.06E+00			2.06E+00					0
Wastewater Injected	2.98E-01			2.98E-01					0
Arsenic	2.61E-09			2.61E-09					0
Benzene	6.28E-08			6.28E-08					0
Boron	1.34E-06			1.34E-06					0
Chloride	1.00E-03			1.00E-03					0
Mobile Ions	3.07E-03			3.07E-03					0
Cadmium	2.14E-08			2.14E-08					0
Chromium	1.94E-09			1.94E-09					0
Mercury	4.88E-10			4.88E-10					0
Thallium	4.61E-10			4.61E-10					0
Solid Wastes									
Resins and membranes				0			1.00E-03		1.00E-03
Sludge				0			2.75E-01		2.75E-01
HCL				0	1.73E-07				1.73E-07
Ammonia				0	2.83E-07				2.83E-07
Coal Ash				0	2.01E-02				2.01E-02
Fly Ash		3.08E-03	4.46E-03	7.54E-03		5.18E-03		6.40E-02	6.92E-02
Bottom Ash		9.18E-04	1.33E-03	2.25E-03		1.54E-03		1.91E-02	2.06E-02
Slag		4.02E-04	5.82E-04	9.84E-04		6.75E-04		8.35E-03	9.02E-03
FGD Solids		1.31E-03	1.90E-03	3.21E-03		2.21E-03		2.73E-02	2.95E-02
Depleted Uranium		2.30E-04	3.33E-04	5.63E-04		3.86E-04		4.78E-03	5.16E-03
Mining Residues	4.54E-07	1.46E-02	2.12E-02	3.58E-02		2.46E-02		3.04E-01	3.28E-01
U238		9.61E-07	1.39E-06	2.35E-06		1.61E-06		1.99E-05	2.16E-05
U236		6.35E-10	9.18E-10	1.55E-09		1.07E-09		1.32E-08	1.42E-08

U235		8.09E-09		1.17E-08	1.98E-08		1.36E-08		1.68E-07	1.82E-07
Pu (fissile)		6.58E-09		9.51E-09	1.61E-08		1.10E-08		1.36E-07	1.48E-07
Pu (nonfissile)		2.53E-09		3.66E-09	6.19E-09		4.25E-09		5.25E-08	5.67E-08
Fission Products		4.60E-09		6.65E-09	1.13E-08		7.73E-09		9.55E-08	1.03E-07
Acetylene			3.16E-04		3.16E-04					0
Formaldehyde			7.41E-04		7.41E-04					0
Copper	1.33E-08		1.15E-05		1.15E-05					0
Nickel			1.21E-06		1.21E-06					0
Butyl alcohol			0.00E+00		0.00E+00					0
Cupriene polymers			8.91E-04		8.91E-04					0
Propionaldehyde			2.31E-05		2.31E-05					0
Acetone			6.49E-05		6.49E-05					0
Toluene			1.32E-02		1.32E-02					0
3-hydroxy-2-methylpropional			5.24E-05		5.24E-05					0
4-hydroxybutyrate			1.09E-04		1.09E-04					0
Methanol	1.33E-08				1.33E-08					0
Resource Consumption										
Coal		4.95E-02		7.15E-02	1.21E-01		2.21E-01		1.25E+00	1.47E+00
Natural Gas	7.10E-01	7.57E-02	1.68E-01	7.22E-01	1.68E+00		8.82E-02		4.54E-01	5.42E-01
LPG					0		7.41E-03			7.41E-03
Petroleum	7.46E-03	2.81E-04		4.06E-04	8.15E-03		3.59E-02		5.48E-03	4.14E-02
Electricity		7.27E-08		1.05E-07	1.78E-07		1.22E-07		1.51E-06	1.63E-06
Sulfur					0	1.37E-02				1.37E-02
Phosphate Rock					0	3.94E-02				3.94E-02
Potassium Chloride					0	1.15E-02				1.15E-02

Soil					0	3.03				3.03
Water	8.38E-02		49.64		49.73	11.51		71.92		83.43
Uranium		7.38E-07		1.07E-06	1.80E-06		1.24E-06		1.53E-05	1.65E-05
Hydropotential		2.72		3.93	6.65		4.57		56.45	61.01
Hydrogen			4.89E-02		4.89E-02				1.20E-01	1.20E-01
Propylene oxide			7.58E-02		7.58E-02					0
CO			3.41E-02		3.41E-02					0
Copper			2.04E-04		2.04E-04					0
Nickel			2.14E-04		2.14E-04					0
Toluene			1.33E-02		1.33E-02					0
n-Methylpyrolidinone	3.32E-04				3.32E-04					0
Land Use	6.31E-07				6.31E-07	1.30E-04				1.30E-04
Energy Consumption										
Coal		594		858	1,452		2,435		13,770	16,205
Natural Gas	16,730	1,786	4,150	17,032	39,698		2,184	0	11,250	13,434
LPG					0		812			812
Uranium		154		223	377		259		3,196	3,454
Hydroelectric		51		74	125		86		1,060	1,145
Petroleum	143	5		8	156		688		105	793
Geothermal		5		7	11		8		93	101
Total	16,873	2,594	4,150	18,201	41,818		6,471		29,474	35,945

Table 5.3. Comparison of Raw (Unweighted) Impact Scores by Criteria for the Convention versus Alternative Feedstock BDO Process[(a)]

Impact Category	CF Process	AF Process
Ozone Depletion	0	0
Global Warming	3.29	3.30[(b)]
Resource Depletion	607	**293**
Acid Rain	**1.3E-02**	2.7E-01
Smog	**2.1E-03**	3.1E-03
Water Use	**49.73**	83.43
PM10	**6.2E-05**	1.4E-02
Human Inhalation Toxicity	**1.4E-01**	5.0E-01
Carcinogenicity	4.3E-04	**2.7E-07**
Solid Waste Disposal/Land Use	**8.1E-06**	4.3E-04
Resource Extraction/Production Land Use	**6.3E-07**	1.3E-04
Terrestrial (wildlife) Toxicity	**1.2E-02**	1.6E-02
Aquatic (fish) Toxicity	**5.6E-03**	3.7E-02
Eutrophication	1.7E-02	2.0E-02

(a) Bold score values indicate the preferred option.

(b) Scores differing by less than 25% are not significantly different.

Table 5.4 Summary Results of Detailed LCA for BDO Process Development

Option	Environmental Characteristics
Conventional Route	♦ Coal is the resource material most heavily used in the conventional process life cycle.
	♦ Energy requirements for the life cycle are met by fuels using electricity generation, steam generation for motive power and process heating, and transportation.
	♦ Methanol and formaldehyde are the largest hazardous airborne releases from the processes preceding BDO manufacturing. Butyl alcohol and acetone are the largest releases from the BDO manufacturing step.
	♦ The carcinogenicity and resource depletion environmental impact categories have greater normalized impact scores than those for the alternative process.
	♦ The conventional and alternative processes are indistinguishable with regard to their global warming potential contributions.
Alternative Route	♦ Natural gas is the resource material most heavily used in the alternative process life cycle.
	♦ Energy requirements for the life cycle are met by fuels using electricity generation, steam generation for motive power and process heating, and transportation.
	• The acid rain, smog, water use, pm10, human inhalation toxicity, solid waste disposal/land use, resource extraction/production land use, and aquatic (fish) toxicity impacts scores for the alternative process are greater than those for the conventional process.

6. Decommissioning

This section describes the consideration of life-cycle environmental factors in the discontinuation, disassembly, decontamination, storage, and disposal of systems, processes, and facilities[4].

6.1 Products and Systems

Most life cycle engineering efforts will be directed at the development or modification of products and systems at the beginning of their life cycle. However, there are numerous systems in place that could benefit from application of an LCE perspective during their retirement and final disposition. In many cases the process and consequences of decommissioning were not considered during the original design engineering effort. LCE of the recovery, disassembly, materials and component recycling activities under these circumstances is less than optimal, but still potentially benefits from application of life cycle thinking.

6.2 Processes and Facilities[5]

Decommissioning of processes and facilities involves a series of steps that can include investigation of technology applicability, pilot or preliminary-scale demonstrations, and application of the technology. The latter includes the life cycle aspects of input materials for cleaning, dismantlement, and final disposition or recycling along with the associated environmental burdens of each activity. An additional source of guidance on the application of LCE for site remediation may be found in Diamond et al. (1999) and Page et al. (1999).

6.3 LCE Case Study: Pantex Facility Decommissioning

The Department of Energy's Pantex Plant is currently in the process of decontaminating structures no longer needed to support its new mission. These structures may include production, administrative or testing facilities. Decommissioning of production and test facilities has the complication of the possibility of mixed – hazardous and radioactive – contamination. Pantex desires to reduce the radioactive decontamination levels of such facilities to *de minimis* levels, which allows for a much larger number of disposal or recycling options. Further, Pantex personnel wish to promote and use more environmentally benign decontamination methods whenever possible. This led to testing of two competing technologies for decontamination of surfaces — Steel Grit Blasting and Crushed Safety Glass Blasting.

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[4] This type of decision is separate and distinct from the end-of-life stage that is considered as one of the life cycle stages of products, systems, processes, and facilities.

[5] Facility decommissioning may also extend to site remediation that likewise involves a series of decisions regarding materials and resources use and efficiency, costs, and technical performance.

6.3.1 Targeting the Assessment

Establishing the Function Being Provided

The basis of performance comparison between the two decontamination technology systems was removal of one μCi-sq.ft. (There are 2.22×10^6 dpm per μCi, and 0.0000929 ft^2 per 100 cm^2.)

Naming the Evaluation Team

The evaluation team for these competing technologies consisted of:

Battelle Life Cycle Management personnel who provided expert LCA skills,

Pantex Plant E, H & S personnel, and

The Team Leader from the technology demonstration contractor who provided expert knowledge on the practices and operation of the technologies.

Developing Requirements and Goals

The purpose of the technology demonstration was to evaluate the potential for either or both of the technologies to satisfactorily decontaminate a radioactively contaminated surface so that the materials could be disposed of or recycled via the standard solid waste management system. The LCA was performed to provide additional information over and above simple performance, and was to supplement the projected cost and performance data collected on site with estimates of overall life cycle environmental burdens. These burdens included a number of standard environmental impacts such as resource consumption, greenhouse gas emissions, and release of toxicants to air, water and solid waste streams.

Proposing Engineering Technology Options

Two alternative technologies were evaluated.

Both technologies make use of materials reclaimed from the waste stream. Each is a media blasting technology, similar to sand blasting, and as such, are optimal for the removal of surface contamination. The prime difference between the systems lies in the blasting media. The Crushed Safety Glass Blasting makes use of safety glass reclaimed from automobiles, trucks, and other sources. The glass is crushed and sorted to size. The steel grit used is slag, a by-product of steel manufacture. The steel grit is also crushed and sorted by size.

The technology in general consists of a large air supply, a hopper that contains blasting media, and a handheld delivery device. In order to minimize wind drift of the spent media and removed material, a small rectangular enclosure measuring about 18 inches on each side was built around the handheld unit. To this unit a vacuum hose was attached. A constant vacuum was applied to the enclosure to capture as much of the fine particulate matter removed material as possible. This stream was passed through a HEPA filter, which served to capture the fine particulate matter, prior to discharge to the atmosphere.

6.3.2 Preliminary Assessment

Defining the Life Cycle

The life cycle for the competing technologies was defined to include all activities from collection of geologic resources, production of virgin materials, collection and processing of the reclaimed or recycled materials, application during the demonstration, through clean up and disposal of residual materials. Transportation of materials was included where required, as was the manufacture, use and disposal of personal protective equipment.

6.3.3 Detailed Assessment

The LCI showed that glass media blasting technology was far superior to the steel grit blast technology from an environmental standpoint. The assessment showed an almost across the board factor of 5.7 times less environmental burdens for the glass media blasting compared to the same criteria for steel grit blasting. Examination of the results by life cycle stage showed that the factor could be directly attributed to the difference in energy consumption in production of the materials required to effect an equivalent radiation removal.

At the same time that the environmental profile clearly identified the glass media blast technology as the preferred alternative, the performance assessment data were less than satisfactory. Given the objective to remove the contamination to a level that would allow the disposal as solid waste, neither technology proved adequate. This finding points out the need in most LCE evaluations for at least one of the alternatives to meet the performance objectives. Upon realizing that the blasting options would not work a third option to cut up the contaminated surfaces into smaller pieces that could be handled as radioactive waste was implemented.

6.4 LCE Case Study: GBU-24 Weapon System Decommissioning

The LCED Energetic Materials Project includes a LCA, which also considers cost and performance, on two DoD weapon systems which use cyclotrimethylenetrinitramine Research Development Explosive (RDX): the GBU-24 earth penetrator and the M-900 projectile. The GBU-24 is a one-ton earth penetrator conventional explosive bomb used by both the US Navy and Air Force. The assembled bomb includes a BLU-109 bomb body filled with PBXN-109 energetic material, an FMU-143 fuse, and a guidance system. PBXN-109 contains RDX in the form of Coated Explosive Material Number 7 (CXM-7), aluminum powder, and various binders and additives. The M-900 is an APFSDS-T cartridge used for the 105 mm gun employed on the M1 Abrams tank. The cartridge is equipped with a depleted uranium penetrator section designed for a muzzle velocity of 1,500 meters per second. The M-900 is made up of a steel case and savoy, depleted uranium penetrator rod, M43 propellant, and a fuse.

6.4.1 Targeting the Assessment

Establishing the Function Being Provided

The functional unit for the assessment was one GBU-24 unit. Each is designed to penetrate up to 6 feet in reinforced concrete.

Naming the Evaluation Team

The evaluation team for this effort consisted of management and technical functions. Members of the team included:

- Battelle Memorial Institute Life Cycle Management staff who are experts in Life Cycle Assessment, and
- Operations personnel at Los Alamos National Laboratory and Holston Army Ammunition Plant.

These groups interacted on a number of occasions. Operations personnel provided inventory data in the form of reports. Battelle assembled the inventory data and provided the impact assessment.

Developing Requirements and Goals

The requirement of the design activity was to guide the improvement of the UPM-880 by improving upon eleven impact metrics relating inventory inputs and outputs to: photochemical smog formation, ozone depletion, acid rain, global warming, eutrophication, carcinogenicity, human inhalation toxicity, wildlife toxicity, fish toxicity, land use, and resource depletion. Requirements were differentiated from goals using the Analytical Hierarchy Process (AHP) as a group exercise by Battelle staff to reflect DoD policy and local site perspective. The team was asked to reach consensus on weighting factors grouped into global, regional and local applicability.

Proposing Engineering Technology Options

Initially, assessments focused on two energetic product streams:

- PBNX-109 explosive in the GBU-24 earth penetrator bomb, and
- M43 propellant in the M-900 armor-penetrating fin-stabilized desheathing savoy.

6.4.2 Preliminary Assessment

Defining the Life Cycle

Modules included in the inventory included:

- geologic and biotic resource extraction (bauxite, coal, iron ore, limestone, natural gas, petroleum),
- Intermediate materials manufacturing (acetic acid, acetone, ammonia, binders, cyclohexanone, dioctyladipate, formaldehyde, hexamine, propyl acetate, trichloroethane, and triphenyl phosphate),
- PBNX-109 synthesis performed at the Holston Army Ammunition Plant (HSAAP) in Kingsport, Tennessee,
- Load, assemble, and pack operations for the GBU-24 performed at the McAlester Army Ammunition Plant (MCAAP) in McAlester, Oklahoma,
- The M43 propellant production at the Indian Head Naval Surface Warfare Center in Indian Head, Maryland (the focus of a separate LCA),
- Demilitarization, and
- Transportation and electricity generation.

6.4.3 Detailed Assessment

Table 6.1 presents the results of the detailed assessment of the GBU. Inventory data were not available to support the determination of contribution to ozone depletion, water use, resource extraction, or land use.

Table 6.1 Detailed Assessment Results

Option	Environmental Characteristics
PBNX-109 Explosive	♦ Coal is the resource material most heavily used in the life cycle.
	♦ Energy requirements for the life cycle are met by fuels using electricity generation, steam generation for motive power and process heating, and transportation.
	♦ Trichloroethane, a hazardous liquid, used for solvent soak operations in DEMIL is the largest DoD facility waste followed by solid residuals from coal-based steam generation plants. Airborne releases are largest for sulfur dioxides, acetic acid, and nitrogen oxides.
	♦ The carcinogenicity environmental impact category shows the greatest normalized impact score when all impacts assessed are assigned equal importance. The carcinogenicity and terrestrial toxicity impact categories contribute 46% and 41% respectively of the total normalized impact scores.
	♦ For a national "policy focused" perspective, carcinogenicity contributes 46% and terrestrial toxicity contributes 38% of the total weighted impact scores. For a "local focused" perspective, carcinogenicity contributes 47% and terrestrial toxicity contributes 39% of the total weighted impact scores.
M43 propellant	♦ Major sources of waste from M43 production include isopropyl shipping fluids, working solvents used in propellant processing, and to a lesser extent, waste propellant.

6.4.4 Developing Specifications

Since the carcinogenicity and terrestrial toxicity impact categories contribute the most to the total impact of the baseline process, the emissions in these categories were considered as a place to focus improvement activities. It was found that the assessment of potential impacts suggested a different plan of action than a "less-is-better" evaluation of the inventory information.

7. References and Additional Resources

1. EPA, 1996. *Life Cycle Assessment for Chemical Agent Resistant Coating*, EPA/600/R-96/104, September 1996, various pagination.
2. SETAC, 1997. *Life Cycle Impact Assessment: The State of the Art*, report of the LCA Impact Assessment Workgroup, Society of Environmental Toxicology and Chemistry, Pensacola FL, Chapter 3, pages 77-82 and Appendix 2.
3. Baumann, H., 1995. *Decision Making and Life Cycle Assessment*, Licentiate Thesis, Technical Environmental Planning Report 1995:4, Swedish Waste Research Council AFR Report 77, Appendix Section 1, page 15-18.
4. SETAC-Europe, 1994. *Integrating Impact Assessment into LCA*, Proceedings of the LCA Symposium held at the Fourth SETAC-Europe Congress, Brussels Belgium, Chapter 4 Valuation Methods, pages 105-160.
5. Lewis, G. and G.A. Keoleian, undated. *Life Cycle Design of Amorphous Silicon Photovoltaic Modules*, prepared for USEPA National Risk Management Research Laboratory, CR822998-01-0, prepared by National Pollution Prevention Center, University of Michigan.
6. Diamond, M.L., C.A. Page, M. Campbell, S. McKenna, and R. Lall, 1999. *Life Cycle Framework for Assessment of Site Remediation Options: Method and Generic Survey,* Environmental Toxicology and Chemistry, 18(4), 788-800.
7. Page, C.A., M.L. Diamond, M. Campbell, and S. McKenna, 1999. . *Life Cycle Framework for Assessment of Site Remediation Options: Case Study*, Environmental Toxicology and Chemistry, 18(4), 801-810.

8. Worksheet Templates

Attachment A: Maintenance Worksheets

ITEM BEING MAINTAINED (name of product, system, process, or facility) MAINTENANCE OPERATION	Life Cycle Engineering Assessment ROUTINE AND UNANTICIPATED MAINTENANCE Project No.	Prepared by: Checked by: Date: Sheet of

WORKSHEET 1: Developing Requirements and Goals

General Information

	Description
Maintenance activity	
Frequency of routine maintenance	
Situation resulting in unanticipated maintenance and preventative measures	
FUNCTIONAL UNIT	

Category	Applicable Life Cycle Stage				Requirements and Goals	Requirement (R) or Goal (G)
	MP	MC	USM	D		
Performance						
Cost						
Environmental – Facility						
Environmental – Local						
Environmental – Regional						
Environmental- Global						

ITEM BEING MAINTAINED (name of product, system, process, or facility) MAINTENANCE OPERATION	Life Cycle Engineering Assessment ROUTINE AND UNANTICIPATED MAINTENANCE Project No.	Prepared by: Checked by: Date: **Sheet** of

WORKSHEET 2: Proposing Technologies and Options

Technology Information

Technology Name	Description	Technology Category*	Desirable Technology Types**

***Technology Categories**
- material (M)
- equipment (E)

****Desirable Technology Types:**
- *materials:* non-regulated (NREG), non-contributory (NC), non-energy intensive (NEI), non-water intensive (NWI), recoverable (REC), treatable as waste (T)
- *equipment::* material efficient (ME), energy efficient (EE), water efficient (WE), material recovery (MR), energy recovery (ER), treatable wastes (TW)

Inclusion of Technologies (Enter quantity per functional unit)

Option Name	Technology 1	Technology 2	Technology 3	Technology 4	Technology 5	Technology 6	Technology 7	
UNITS								
CONFIGURATION STATUS simplified (SIMP), accessible (ACC), modular (MOD), joining status (JS)								

ITEM BEING MAINTAINED (name of product, system, process, or facility) **MAINTENANCE OPERATION**	**Life Cycle Engineering Assessment** **ROUTINE AND UNANTICIPATED MAINTENANCE** Project No.	Prepared by: Checked by Date: **Sheet of**

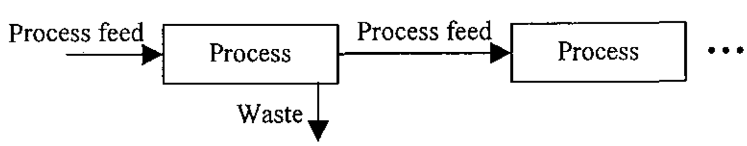
WORKSHEET 3: Defining the Technology Life Cycle

Technology Description

Technology	
Additional material and equipment requirements	
Maintenance procedures	

Material Production
Technology Manufacturing
Maintenance Activity
Material Recovery and Disposal

Key:



ITEM BEING MAINTAINED (name of product, system, process, or facility) MAINTENANCE OPERATION	Life Cycle Engineering Assessment ROUTINE AND UNANTICIPATED MAINTENANCE Project No.	Prepared by : Checked by Date: Sheet of

WORKSHEET 4: Linking Technologies to Requirements and Goals

Status of Achievement

Requirements and Goals	Req't (R) or Goal (G)	Technology 1	Technology 2	Technology 3	Technology 4	Technology 5	Technology 6	Technology 7	COUNT +/-
Performance									
Cost									
Environmental - Facility									
Environmental -Local									
Environmental - Regional									
Environmental - Global									
COUNT + REQUIREMENTS / GOALS		/	/	/	/	/	/	/	
COUNT - REQUIREMENTS / GOALS		/	/	/	/	/	/	/	

Key: + Technology meets the requirement or goal. ? More information is needed.
- Technology does not meet the requirement or goal. NA Not Applicable to requirement or goal.

ITEM BEING MAINTAINED (name of product, system, process, or facility) MAINTENANCE OPERATION	Life Cycle Engineering Assessment **ROUTINE AND UNANTICIPATED MAINTENANCE** Project No.	Prepared by: Checked by: Date: **Sheet** of

WORKSHEET 5: Linking Options to Requirements and Goals

Degree of Achievement

Requirements and Goals	Req't (R) or Goal (G)	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6
Performance							
Cost							
Environmental - Facility							
Environmental – Local							
Environmental - Regional							
Environmental – Global							
COUNT E REQUIREMENTS/GOALS		/	/	/	/	/	/
COUNT M REQUIREMENTS/GOALS		/	/	/	/	/	/
COUNT FS REQUIREMENTS/GOALS		/	/	/	/	/	/
COUNT FC REQUIREMENTS/GOALS		/	/	/	/	/	/

Key:

- E — Option considerably EXCEEDS the requirement or goal.
- M — Option MEETS the requirement or goal without considerably exceeding it.
- FS — Option FAILS to meet the requirement or goal by a SLIGHT margin.
- FC — Option FAILS to meet the requirement or goal by a CONSIDERABLE margin.
- ? — More information is needed to determine the achievement status of the option.

Attachment B: Upgrades Worksheets

ITEM BEING UPGRADED (name of product, system, process, or facility) **MANUFACTURING/URM/ DISPOSAL OPERATION BOUNDARY:**	**Life Cycle Engineering Assessment** **UPGRADING** Project No.	Prepared by: Checked by: Date: **Sheet** of

WORKSHEET 1: Developing Requirements and Goals

General Information

	Description
Activities or operations being upgraded	
Frequency of upgrade	
Reason for examining upgrade measures	
FUNCTIONAL UNIT	

Category	Applicable Life Cycle Stage				Requirements and Goals	Requirement (R) or Goal (G)
	MP	MC	USM	D		
Performance						
Cost						
Environmental – Facility						
Environmental – Local						
Environmental – Regional						
Environmental- Global						

ITEM BEING UPGRADED (name of product, system, process, or facility)	Life Cycle Engineering Assessment UPGRADING Project No.	Prepared by: Checked by: Date: Sheet of

WORKSHEET 2: Proposing Technologies and Options

Technology Information

Technology Name	Description	Technology Category*	Desirable Technology Types**

*Technology Categories
- material (M)
- equipment (E)

**Desirable Technology Types:
- *materials:* non-regulated (NREG), non-contributory (NC), non-energy intensive (NEI), non-water intensive (NWI), recoverable (REC), treatable as waste (T)
- *equipment:*: material efficient (ME), energy efficient (EE), water efficient (WE), material recovery (MR), energy recovery (ER), treatable wastes (TW)

Inclusion of Technologies (Enter quantity per functional unit)

Option Name	Technology 1	Technology 2	Technology 3	Technology 4	Technology 5	Technology 6	Technology 7	
UNITS								
CONFIGURATION STATUS Simplified (SIMP), accessible (ACC), modular (MOD), joining status (JS)								

ITEM BEING UPGRADED (name of product, system, process, or facility)	Life Cycle Engineering Assessment UPGRADING Project No.	Prepared by: Checked by Date: **Sheet** of

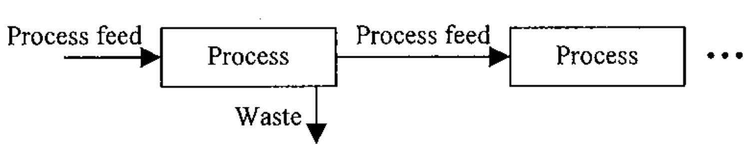
WORKSHEET 3: Defining the Technology Life Cycle

Technology Description

Technology	
Additional material and equipment requirements	
Manufacturing and operational support procedures	

Material Production
Technology Manufacturing
Maintenance Activity
Material Recovery and Disposal

Key:



ITEM BEING UPGRADED (name of product, system, process, or facility)	Life Cycle Engineering Assessment **UPGRADES** Project No.	Prepared by : Checked by Date: **Sheet** of

WORKSHEET 4: Linking Technologies to Requirements and Goals

Status of Achievement

Requirements and Goals	Req't (R) or Goal (G)	Technology 1	Technology 2	Technology 3	Technology 4	Technology 5	Technology 6	Technology 7	COUNT +/-
Performance									
Cost									
Environmental - Facility									
Environmental -Local									
Environmental - Regional									
Environmental - Global									
COUNT + REQUIREMENTS / GOALS		/	/	/	/	/	/	/	
COUNT - REQUIREMENTS / GOALS		/	/	/	/	/	/	/	

Key:
- \+ Technology meets the requirement or goal.
- \- Technology does not meet the requirement or goal.
- ? More information is needed.
- NA Not Applicable to requirement or goal.

ITEM BEING UPGRADED (name of product, system, process, or facility)	**Life Cycle Engineering Assessment** **UPGRADES** Project No.	Prepared by: Checked by: Date: **Sheet** of

WORKSHEET 5: Linking Options to Requirements and Goals

Degree of Achievement

Requirements and Goals	Req't (R) or Goal (G)	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6
Performance							
Cost							
Environmental - Facility							
Environmental – Local							
Environmental - Regional							
Environmental – Global							
COUNT E REQUIREMENTS/GOALS		/	/	/	/	/	/
COUNT M REQUIREMENTS/GOALS		/	/	/	/	/	/
COUNT FS REQUIREMENTS/GOALS		/	/	/	/	/	/
COUNT FC REQUIREMENTS/GOALS		/	/	/	/	/	/

Key:

- E — Option considerably EXCEEDS the requirement or goal.
- M — Option MEETS the requirement or goal without considerably exceeding it.
- FS — Option FAILS to meet the requirement or goal by a SLIGHT margin.
- FC — Option FAILS to meet the requirement or goal by a CONSIDERABLE margin.
- ? — More information is needed to determine the achievement status of the option.

Attachment C: New Design Worksheets

ITEM BEING DEVELOPED (name of product, system, process, or facility) OPERATION OR ACTIVITY BOUNDARY DESCRIPTION	Life Cycle Engineering Assessment NEW PRODUCT, SYSTEM, PROCESS OR FACILITY DESIGN Project No.	Prepared by: Checked by: Date: **Sheet** of

WORKSHEET 1: Developing Requirements and Goals

General Information

	Description
Activities or operations involved	
Item or service being replaced or enhanced	
Reason for new design	
FUNCTIONAL UNIT	

Category	Applicable Life Cycle Stage				Requirements and Goals	Requirement (R) or Goal (G)
	MP	MC	USM	D		
Performance						
Cost						
Environmental – Facility						
Environmental – Local						
Environmental – Regional						
Environmental- Global						

ITEM BEING DEVELOPED (name of product, system, process, or facility)	Life Cycle Engineering Assessment NEW PRODUCT, SYSTEM, PROCESS, OR FACILITY Project No.	Prepared by: Checked by: Date: Sheet of

WORKSHEET 2: Proposing Technologies and Options

Technology Information

Technology Name	Description	Technology Category*	Desirable Technology Types**

***Technology Categories**
- material (M)
- equipment (E)

****Desirable Technology Types:**
- *materials:* non-regulated (NREG), non-contributory (NC), non-energy intensive (NEI), non-water intensive (NWI), recoverable (REC), treatable as waste (T)
- *equipment:*: material efficient (ME), energy efficient (EE), water efficient (WE), material recovery (MR), energy recovery (ER), treatable wastes (TW)

Inclusion of Technologies (Enter quantity per functional unit)

Option Name	Technology 1 MIL-P53022	Technology 2 MIL-P53030	Technology 3 MIL-T81772	Technology 4 AA-857-B	Technology 5 Std. spray gun	Technology 6 Alt. spray gun	Technology 7 Alt. gun bath	Topcoat
UNITS								
CONFIGURATION STATUS simplified (SIMP), accessible (ACC), modular (MOD), joining status (JS)								

ITEM BEING DEVELOPED (name of product, system, process, or facility)	Life Cycle Engineering Assessment NEW PRODUCT, SYSTEM, PROCESS, OR FACILITY Project No.	Prepared by: Checked by Date: **Sheet** of

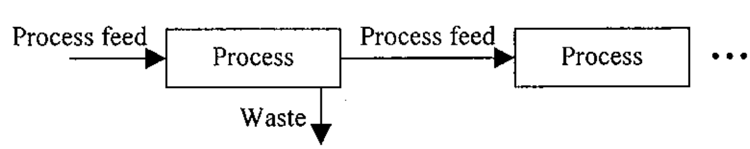
WORKSHEET 3: Defining the Technology Life Cycle

Technology Description

Technology	
Additional material and equipment requirements	
Maintenance and operational procedures	

Material Production
Technology Manufacturing
Maintenance Activity
Material Recovery and Disposal

Key:



ITEM BEING DEVELOPED (name of product, system, process, or facility)	Life Cycle Engineering Assessment NEW PRODUCT, SYSTEM, PROCESS, OR FACILITY Project No.	Prepared by : Checked by Date: Sheet of

WORKSHEET 4: Linking Technologies to Requirements and Goals

Status of Achievement

Requirements and Goals	Req't (R) or Goal (G)	Technology 1	Technology 2	Technology 3	Technology 4	Technology 5	Technology 6	Technology 7	COUNT +/-
Performance									
Cost									
Environmental - Facility									
Environmental -Local									
Environmental - Regional									
Environmental - Global									
COUNT + REQUIREMENTS / GOALS		/	/	/	/	/	/	/	
COUNT - REQUIREMENTS / GOALS		/	/	/	/	/	/	/	

Key:
+ Technology meets the requirement or goal.
- Technology does not meet the requirement or goal.
? More information is needed.
NA Not Applicable to requirement or goal.

ITEM BEING DEVELOPED (name of product, system, process, or facility)	Life Cycle Engineering Assessment NEW PRODUCT, SYSTEM, PROCESS, OR FACILITY Project No.	Prepared by: Checked by: Date: **Sheet** of

WORKSHEET 5: Linking Options to Requirements and Goals

Degree of Achievement

Requirements and Goals	Req't (R) or Goal (G)	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6
Performance							
Cost							
Environmental - Facility							
Environmental – Local							
Environmental - Regional							
Environmental – Global							
COUNT E REQUIREMENTS/GOALS		/	/	/	/	/	/
COUNT M REQUIREMENTS/GOALS		/	/	/	/	/	/
COUNT FS REQUIREMENTS/GOALS		/	/	/	/	/	/
COUNT FC REQUIREMENTS/GOALS		/	/	/	/	/	/

Key:

- E — Option considerably EXCEEDS the requirement or goal.
- M — Option MEETS the requirement or goal without considerably exceeding it.
- FS — Option FAILS to meet the requirement or goal by a SLIGHT margin.
- FC — Option FAILS to meet the requirement or goal by a CONSIDERABLE margin.
- ? — More information is needed to determine the achievement status of the option.

Attachment D: Decommissioning Worksheets

ITEM BEING DECOMMISSIONED (name of product, system, process, or facility) **DECOMMISSIONING ACTIVITY:**	**Life Cycle Engineering Assessment** **DECOMMISSIONING** Project No.	Prepared by: Checked by: Date: **Sheet** of

WORKSHEET 1: Developing Requirements and Goals

General Information

	Description
Activities or operations associated with decommissioning	
Reason for decommissioning	
FUNCTIONAL UNIT	

Category	Applicable Life Cycle Stage				Requirements and Goals	Requirement (R) or Goal (G)
	MP	MC	USM	D		
Performance						
Cost						
Environmental – Facility						
Environmental – Local						
Environmental – Regional						
Environmental- Global						

ITEM BEING DECOMMISSIONED (name of product, system, process, or facility)	Life Cycle Engineering Assessment DECOMMISSIONING Project No.	Prepared by: Checked by: Date: **Sheet** of

WORKSHEET 2: Proposing Technologies and Options

Technology Information

Technology Name	Description	Technology Category*	Desirable Technology Types**

***Technology Categories**
- material (M)
- equipment (E)

****Desirable Technology Types:**
- *materials:* non-regulated (NREG), non-contributory (NC), non-energy intensive (NEI), non-water intensive (NWI), recoverable (REC), treatable as waste (T)
- *equipment::* material efficient (ME), energy efficient (EE), water efficient (WE), material recovery (MR), energy recovery (ER), treatable wastes (TW)

Inclusion of Technologies (Enter quantity per functional unit)

Option Name	Technology 1	Technology 2	Technology 3	Technology 4	Technology 5	Technology 6	Technology 7	
UNITS								
CONFIGURATION STATUS Simplified (SIMP), accessible (ACC), modular (MOD), joining status (JS)								

ITEM BEING DECOMMISSIONED (name of product, system, process, or facility)	**Life Cycle Engineering Assessment** **DECOMMISSIONING** Project No.	Prepared by: Checked by Date: **Sheet** of

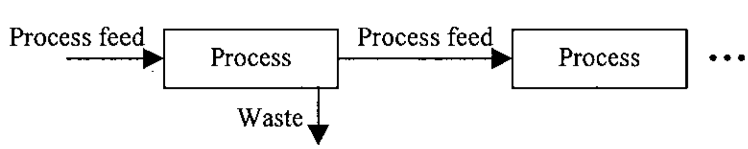
WORKSHEET 3: Defining the Technology Life Cycle

Technology Description

Technology	
Additional material and equipment requirements	
Manufacturing and operational support procedures	

Material Production
Technology Manufacturing
Maintenance Activity
Material Recovery and Disposal

Key:



ITEM BEING DECOMMISSIONED (name of product, system, process, or facility)	Life Cycle Engineering Assessment DECOMMISSIONING Project No.	Prepared by : Checked by Date: Sheet of

WORKSHEET 4: Linking Technologies to Requirements and Goals

Status of Achievement

Requirements and Goals	Req't (R) or Goal (G)	Technology 1	Technology 2	Technology 3	Technology 4	Technology 5	Technology 6	Technology 7	COUNT +/-
Performance									
Cost									
Environmental - Facility									
Environmental -Local									
Environmental - Regional									
Environmental - Global									
COUNT + REQUIREMENTS / GOALS		/	/	/	/	/	/	/	
COUNT - REQUIREMENTS / GOALS		/	/	/	/	/	/	/	

Key:				
Key:	+	Technology meets the requirement or goal.	?	More information is needed.
	-	Technology does not meet the requirement or goal.	NA	Not Applicable to requirement or goal.

ITEM BEING DECOMMISSIONED (name of product, system, process, or facility)	Life Cycle Engineering Assessment **DECOMMISSIONED** Project No.	Prepared by: Checked by: Date: **Sheet** of

WORKSHEET 5: Linking Options to Requirements and Goals

Degree of Achievement

Requirements and Goals	Req't (R) or Goal (G)	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6
Performance							
Cost							
Environmental - Facility							
Environmental – Local							
Environmental - Regional							
Environmental – Global							
COUNT E REQUIREMENTS/GOALS		/	/	/	/	/	/
COUNT M REQUIREMENTS/GOALS		/	/	/	/	/	/
COUNT FS REQUIREMENTS/GOALS		/	/	/	/	/	/
COUNT FC REQUIREMENTS/GOALS		/	/	/	/	/	/

Key:

E	Option considerably EXCEEDS the requirement or goal.	FS	Option FAILS to meet the requirement or goal by a SLIGHT margin.
M	Option MEETS the requirement or goal without considerably exceeding it.	FC	Option FAILS to meet the requirement or goal by a CONSIDERABLE margin.
		?	More information is needed to determine the achievement status of the option.