LIFE CYCLE FRAMEWORK
FOR
CONTAMINATED SITE
REMEDIATION OPTIONS

Final Report

AUGUST 1998

Ontario

**Ministry
of the
Environment**

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FOR
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Final Report

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EXECUTIVE SUMMARY

To address broader concerns arising from contaminated site remediation, a Life-Cycle Framework (LCF) has been developed that is comprised of two parts, a qualitative Life-Cycle Management (LCM) approach and a more rigorous, quantitative Life-Cycle Assessment (LCA) approach. The objective of examining site remediation options using the LCF is to consider a wide range of potential environmental and human health impacts beyond the contaminated site *per se*, and over a long time horizon. The approach is intended to provide information that will assist the public, policy makers, land holders, and technology vendors with making decisions protective of environmental and human health by means of minimizing overall environmental burden. LCF can be applied in two ways, to design a remediation project that minimizes environmental burden or to analyze results from previous remediation projects with the aim of identifying opportunities to decrease impacts or increase awareness of impacts.

Application of existing LCA and LCM methods to site remediation options required several adaptations and innovations. The LCM has four stages. *Identify* involves specifying the purpose of the study, the end users, and establishing boundaries. The remedial option is characterized according to life-cycle stages: (i) raw materials and energy acquisition; (ii) site processing; and (iii) post-site processing; with sub-stages (iv) transportation and distribution; (v) waste management; and (vi) monitoring. *Inform* requires compiling an inventory of inputs and outputs based on life-cycle stages and linking inventory items with potential impacts. Stressors, or inventory items that can induce environmental impacts, are grouped in the three categories of pollution, depletion and disturbance. Within each category we distinguish between process- and site-related impacts. Stressors are ranked in a "Potential Impacts Checklist" according to level of concern. In *Assess*, consideration is given to future study according to the purposes established in *Identify*. *Implement* involves acting on the conclusions of the study.

The LCA method was adapted to site remediation options by defining a prolonged temporal boundary of, for example, 25 years that is intended to capture long term impacts and amortize impacts occurring intensively over a short time period (e.g., soil washing) versus those occurring over a long time (e.g., no-action, or encapsulation). The system boundary was defined to include soil, as in LCA for agriculture. Although an obvious functional unit or normalizing factor was not

apparent, we suggest using land mass or volume that is exposed to a remediation option, e.g., the mass of contaminated soil that is delineated. We use the concept of "exposed" because the volume of contaminated soil may not be treated (no-action). The remediation option is broken down into life-cycle stages and an *Inventory* of inputs and outputs is compiled for each stage. *Impact Assessment* involves quantitatively translating inventory items or stressors into potential impacts. Stressors are categorized according to the three impact categories listed above, for process- and site-related impacts. The few impact models that are available for quantitative translation include Global Warming Potential, Acidification Potential, Solid Waste Burden, Land Use, Human and Ecosystem Toxicity for emissions, and Residual Human Toxicity Burden for contaminants remaining on-site in soil and groundwater.

The LCM was used to examine six generic site remediation options: no-action, the risk management approach of encapsulation, excavation and disposal, in-situ methods of vapour extraction and bioremediation, and ex-situ soil washing. Process flow diagrams were developed for each option according to life-cycle stages and sub-stages. A qualitative inventory was developed based on the flow diagrams. Inventory items were linked to potential environmental and human health impacts using the "Potential Impacts Checklist" to identify possible concerns. Three levels of concern were assigned to each stressor for each of the six remediation options according to five criteria. Bias in the ranking process was minimized by conducting initial, independent assessments by multiple appraisers and then reaching consensus on all rankings.

The analysis revealed that concerns with no-action lie in contaminants remaining on-site with potential for off-site migration. Land use is impaired and toxicological concerns are high. Encapsulation minimizes exposure and off-site migration at the detriment of land use potential and site disturbance (e.g., aquifer quality and quantity, land stagnation). On- and off-site toxicity is a concern since contaminant concentrations are not altered. Excavation and off-site disposal minimizes on-site toxicity and maximizes land use potential at the expense of land disturbance at waste disposal facilities and the borrow pit from which clean backfill is obtained. Impacts occur due to the transportation of contaminated soil to the disposal facility and backfill from the borrow pit. Concerns with bioremediation arise from the prolonged time taken for remediation, during which toxicity and/or off-site migration could occur. Soil quality may be improved, but adverse impacts could occur to ground- and surface waters as nutrients and other chemicals are added to enhance contaminant degradation rates. Soil washing results in transportation-related emissions produced by excavation (similarly to excavation and disposal), changes to soil quality that affect land use, land consumption as contaminated fines require disposal, and land disturbance from obtaining clean backfill at a borrow pit. As for bioremediation, concerns with vapour extraction relate to the length of the process leading to potential for toxicity and off-site migration. Land may be consumed by solid waste disposal from water and air treatment.

The LCA was applied to examine potential environmental and human health impacts arising from a case study involving the clean-up of a lead-contaminated site in southern Ontario by means of excavation and disposal. The analysis was based on proprietary consultants' reports. The process involved three main site processing steps of site excavation, backfilling and capping (the latter pertained to part of the site). Five categories of raw materials were acquired (e.g., crude oil for the asphalt cap), waste management involved six steps (e.g., dust mitigation and water treatment), and monitoring occurred at two main stages (site excavation and water treatment). On- and off-site transportation occurred throughout the process. Inventory items were quantified for the four life-cycle stages of raw materials acquisition, site processing, waste management and transportation. Impacts were estimated using stressor-impact models for the process-related indicators of Global Warming Potential, Solid Waste Burden and Ecological and Human Toxicity Potential, and the site-related indicators of Land Use and Residual Human Toxicity Burden. Chemical emissions were related to potential toxicity impacts using a Mackay Level III multimedia model for southern Ontario, adapted for metals. Estimated concentrations were compared to "no-effect" doses using standard intake rates and body weight for human toxicity, and "no-effect" concentrations for ecotoxicity. Residual Human Toxicity Burden was determined by comparing measured chemical concentrations corrected for background concentrations, with a chemical concentration derived from a Reference or Risk Specific Dose, depending on the toxicological mode of action.

The results of the analysis indicated impacts occurring due to transportation-related emissions and energy consumption, as contaminated soil and sludge from water treatment was transported to hazardous and non-hazardous disposal facilities. Solid waste production led to land consumption at two sites (hazardous and non-hazardous disposal facilities), bringing the total number of disturbed sites to four (the contaminated site and borrow pit for backfill in addition to the disposal sites). However, restored land use at the remediated site was greater than that consumed for disposal or disturbed for clean fill due to economies achieved at these sites. Potential human and ecosystem toxicity arose from emissions during excavation of dust with elevated metal concentrations. The greatest concern was due to lead affecting aquatic ecosystem health. The analysis of Residual Human Toxicity Burden indicated concern over lead remaining in soil in two of three areas.

Overall, application of the LCM and LCA to site remediation options suggested that the analysis was useful for identifying potential impacts, some of which are discounted in traditional assessments (e.g., off-site impacts) or not included (e.g., resource consumption, land fragmentation). The analysis also illustrated that site remediation activities result in impacts that occur at the local, regional and global scales, over all activities and locations affected by remediation activities. The LCF provides a systematic method for documenting, displaying and assessing a wide range of impacts issuing from site remediation options, from which more informed decisions can be made that are protective of human and ecosystem health.

ACKNOWLEDGMENTS

Numerous individuals and organizations have contributed to this research project. The Ontario Ministry of Environment and Energy funded the project through the Research Advisory Committee, with Doug Vallery as the project administrator. Ron Lall, now an environmental consultant, was our Scientific Adviser on behalf of the Ministry, followed by Gilles Castonguay of the Technical Services Branch of the Ministry. Both provided critical advice and assistance. Beth Benson, of the Waterfront Regeneration Trust, was instrumental at key points in the project, including its initiation.

The project benefited from advice and discussions held during two workshops. The first workshop was organized by Ron Lall in the winter of 1996 at the Ministry of Environment and Energy and concerned methods of assessing toxicological impacts. It was attended by Ministry experts Lee Hoffman, Al Kuja, Angela Li-Muller and Marius Marsh. A second workshop was held in May 1996 at the University of Toronto. The workshop was organized by Cynthia Page with assistance from Christine Little. The List of Attendees follows below.

We were fortunate to obtain detailed reviews of aspects of the project from Steve Young of the Demeter Group and Gary Pringle of Holocene Consulting. Numerous individuals from the City of Toronto assisted with their expertise, notably Wayne Moss and Franca Ursitti.

The authors would like to thank the staff and colleagues of the Department of Geography, University of Toronto, Metro Toronto Teaching Health Units, and the Environmental Protection Office of the City of Toronto.

Finally, we thank Judy Josefowicz for assistance with data gathering and Julie Phillips and Judy Josefowicz with preparation of the final report.

PEER REVIEW WORKSHOP
May 24th, 1996 University of Toronto

Peer Review Workshop Participants

Beth Benson	Waterfront Regeneration Trust
Roger Bywater	Imperial Oil
Kevin Brady	Environment Canada, now with the Demeter Group
Monica Campbell	Metro Toronto Teaching Health Units, City of Toronto
Nick Colella	Toronto Transit Commission
Miriam Diamond	University of Toronto, Department of Geography and Planning
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1. INTRODUCTION

1.1 BACKGROUND

In urban and industrial areas across Canada, many sites that were used for industrial purposes are now underutilized or derelict. Communities are concerned about potential human and ecosystem health effects that could result from site contamination and related clean-up activities. The issues of site remediation, with associated liability and uncertainty, and potential costs for clean-up, can be significant impediments to redevelopment. Under previous site decommissioning guidelines of the Ontario Ministry of Environment [MOE 1989], many sites were remediated using excavation and disposal. The newer guidelines of the Ministry [MOEE 1996a] provide a wider range of options, including site-specific risk assessment and risk management, and promote treatments such as bioremediation, vapour extraction and thermal desorption, rather than removal of contaminated soils. Policy development, aimed at protecting public and ecological health, has not thoroughly examined risks associated with site remediation processes (i.e., remediation itself entails risks) and impacts beyond the contaminated site. In order to more fully consider and protect public and ecological health, we suggest that policy-makers, remediation practitioners, and the public should be aware of the wider potential impacts of the various remediation options and incorporate this information into their choices for suitable remediation options.

The framework presented here was developed to examine issues related to broad impacts of site remediation processes. It is based on the Life-Cycle (LC) concept that has been most often applied to products rather than processes. "Life-cycle thinking" involves considering all inputs and outputs related to a product or process, from start-to-finish or cradle-to-grave. The method is attractive because it is comprehensive and inclusive, and promotes a holistic approach to minimizing environmental impacts.

The following report details the development and application of a Life-Cycle Framework (LCF) to site remediation options. The LCF consists of two parts, a qualitative Life-Cycle Management (LCM) approach and a quantitative Life-Cycle Assessment (LCA) approach. Condensed versions of the report have been published in the scientific literature [Diamond et al., 1998, Page et al., 1998].

1.2 OBJECTIVES

This study is a first step in investigating whether a Life-Cycle Management (LCM) or Life-Cycle Assessment (LCA) approach is useful for providing information for decision making purposes on a site-specific basis, and consequently of use to private and public sector development proponents.

The project's objectives, along with the main research questions to be addressed, are as follows:

1. Develop a broad framework, based on the "life-cycle concept", for assessing and comparing soil and groundwater remediation options.
2. Refine the broad framework through preliminary application to six generic site remediation options. Questions to aid in this conceptual assessment include:
    - What does the application of the framework tell us about various technologies? Is this information useful from an environmental management policy perspective?
    - What does the application of the framework tell us about a comparison between technologies?
    - What issues arise when applying the framework?
3. Assess the framework through application to a site remediation case study using quantitative data from a completed remediation project. Guiding questions include:
    - What can we learn about the remediation process assessed?
    - What problems/strengths of the framework were encountered?
    - What are the most appropriate applications of the framework?
4. How should the information, gained by applying the LC framework to site remediation activities, be used:
    - to clarify impacts among site remediation options on a comparative/decision-making basis?
    - to inform environmental and public health policy development as related to site remediation options?

    - to assist policy makers and the public in areas of environmental remediation, environmental management, and environmental and public health?

1.3 PROJECT OUTLINE

1.3.1 Life-Cycle Framework for Site Remediation Options

This report is organized into three main sections contained in Chapters 2 to 4, preceded by this introductory chapter. Each of Chapters 2 to 4 can be read independently, without relying on previous information. Chapter 2 contains a detailed description of the method of the Life-Cycle Framework for site remediation options: the development of a life-cycle based approach for generic site remediation options and refining an LCA-based tool for a more detailed life-cycle investigation of remediation activities. Sub-tasks included identifying life-cycle stages in site remediation options; setting appropriate geographic, temporal, and process boundaries; outlining methods for compiling energy and material inventories for the life-cycle stages of the case studies; and determining the environmental and health indicators for site remediation options. The impact assessment portion has been expanded to encompass indicators appropriate for remedial options. In order to strengthen the analysis of environmental and health impacts, possible measures of environmental and human toxicity are also explored.

1.3.2 Application of Life-Cycle Framework to Site Remediation Options

Chapter 3 presents the application of the LC Framework to evaluate the following contaminated site remediation options:

1. control (i.e., no-action)
2. management (e.g., encapsulation)
3. off-site disposal (e.g., excavation and disposal or "dig-and-haul")
4. in-situ bioremediation
5. soil washing
6. vapour extraction

We introduce the qualitative "Potential Impacts Checklist" and the concept of process- and site-related stressors to aid in assessing the potential impacts of each option.

1.3.3 Application of Life-Cycle Approach to a Case Study

In Chapter 4, we apply the LCM and LCA approaches to a contaminated site remediation case study in southern Ontario. The case study, used to assess the Life-Cycle Framework and LCA tools, involves compiling energy and material inventories for the life-cycle stages and determining environmental and health impacts. Inventory items are translated into quantitative potential environmental and health impacts using several impact models. We have contributed to the development of human and ecosystem toxicity impact models for use with process-related contaminant emissions and contaminants remaining on-site in soil and groundwater.

1.3.4 Peer Review Workshops

Peer reviews during the process of conducting the study, in the form of workshops, were held to evaluate the generic approach and critique the data gathered and estimated in the inventory stage for the case study. The final version of the LC approach and its application to six options, and the case study were also reviewed by experts.

1.4 ISSUES IN SITE REMEDIATION

1.4.1 Regulations

Under the Ontario Ministry of Environment's (MOE) 1989 guidelines and waste regulations, "dig-and-haul" was the most popular site remediation option used. Importantly, this includes disposing of the contaminated soil at landfill sites and long-term monitoring at those sites to ensure physical and chemical stability.

New policies of the Ontario Ministry of Environment and Energy (MOEE) have been promulgated with revised guidelines for more chemicals, and are oriented towards treating soil and groundwater contamination rather than opting for complete removal and off-site disposal. Under these site decommissioning guidelines [MOEE 1996a], alternatives for site clean-up might include:

1. complete remediation of all soils that exceed the generic guidelines applicable at surface;
2. remediation of soils that do not meet surficial guidelines in the upper soil strata, and that do not meet generic guidelines applicable at depth; and
3. remediation of soils that do not meet site-specific risk assessment based guidelines.

Policy development, directed towards protecting public and ecological health, has not examined the risk associated with site remediation processes. Though remediation itself entails risk, policy has not examined this risk in the broader geographical context, nor the activities associated with clean-up. To fully protect public and ecological health when attempting to reduce risk in one geographic location, the potential increased risk at a larger scale and over a longer time frame must also be considered. Consequently, many aspects of the entire remediation process, including the time frame of clean-up, receiver of contaminated soils, transportation issues, increased mobility of contaminants due to excavation, etc., should also be examined.

1.4.2 Choosing a Technology

The choice of a remediation technology may be influenced by the public and regulatory pressures mentioned above, as well as by a desire to minimize potential impacts on ecosystem and human health. In addition, there exist several other factors that may influence the choice of a remediation technology. Cost is one of the most significant factors considered by development proponents when reviewing remediation options. The expected duration of a site clean-up is of importance, especially if considering imminent redevelopment or rezoning of a site. As well, some remediation methods have a greater ease of regulatory approval than others.

To assist a community in making informed decisions concerning soil remediation options, the potentially wider impacts of the options considered must first be made clear. These wider impacts necessarily include those beyond the confines of the particular site. The community should be viewed in a bioregional sense, including those affected by the disposal of contaminated soil and other aspects of remediation, those in close proximity to the contaminated site, and others who could be affected by off-site migration.

1.5 LIFE-CYCLE ASSESSMENT (LCA)

1.5.1 LCA Method

LCA is a method for examining the "cradle-to-grave" impacts of a product or process. LCA involves building an inventory of inputs and outputs, and qualitatively and quantitatively evaluating the impacts of that inventory. The process leads to identifying significant aspects of the system that contribute most to the environmental burden of the product or process. Although practiced since the early 1970s, LCA is currently under rapid development and expanded application for a variety of purposes. LCA provides a framework for comprehensively analyzing the impacts associated with a product or process, and can provide a rational, defensible and reproducible basis for decisions taken to minimize environmental and health impacts.

Life-Cycle Assessment is an area addressed in the ISO 14000 series for environmental management. The ISO 14000 environmental management standards are being developed by the International Standards Organization (ISO) to enable the integration of environmental management with business decisions and operations. These guidelines are generic and may be adapted to a company's specific needs, and are an additional method of promoting environmental protection through internal corporate standards.

Life-Cycle Assessment models are used as frameworks when developing assessments of a system. In this project we are following the methods established by the Society of Environmental Toxicology and Chemistry (SETAC), the Canadian Standards Association (CSA), and the U.S. Environmental Protection Agency (U.S. EPA). The four main components of LCA include: Goal Definition or Initiation; Inventory; Impact Assessment; and Improvement Analysis or Interpretation Assessment [SETAC 1991, U.S. EPA 1992, CSA 1994, SETAC 1993a,b]. The components are described in the next section.

There are advantages and disadvantages to LCA that depend on its intended use and how it is conducted. The advantages of LCA are that it provides a systematic framework for assembling all activities and impacts associated with a product or process. The framework also facilitates comparison of disparate processes or activities, and avoids emphasis on sources perceived to be most important due to risk perception or economic concerns. The disadvantages include the dependence of the results on numerous boundaries that are drawn and assumptions made, and the effort and expense involved with undertaking a thorough LCA. Some LCA practitioners are coming to believe that LCA's strength lies in objectively and quantitatively considering all major aspects in the life cycle of a product or process (i.e. inventory), but that using it to make definite choices or comparisons is fraught with problems.

The method for the inventory stage of LCA is presently well established [SETAC 1991, U.S. EPA 1992, CSA 1994]. The method for the impact assessment component, however, is under development. The impact assessment, which may be quantitative and/or qualitative, should address environmental considerations from human and ecosystem perspectives, habitat modification, and other effects. Several impact assessment methods may be applied depending on the type and duration of the effect, geographic scale and, importantly, the level of interpretive accuracy required.

1.5.2 LCA Components

The LCA components are given schematically in Figure 1-1 and are briefly described below.

GOAL DEFINITION OR INITIATION

The purpose and scope of the Life-Cycle Assessment are outlined at the onset of the study. The problem is defined by setting geographic and spatial boundaries, as well as boundaries of the life cycle of the process. For example, assessment is usually restricted to primary activities (e.g., air emissions from processing equipment). Secondary effects that are related to the life cycle but not to the direct use of equipment are commonly neglected for practical purposes (e.g., environmental emissions that arise during the manufacturing of processing equipment). In other words, in this stage one specifies what will and will not be included in the study.

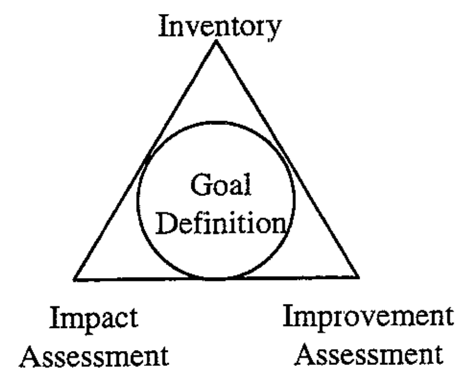

Figure 1-1 Components of Life-Cycle Assessment[1]

INVENTORY

All inputs and outputs of energy and materials are quantified within the established boundaries. The life-cycle inventory (LCI) may consist of the following major stages: raw materials and energy acquisition, processing, distribution and transportation, use/re-use/maintenance, recycle and waste management [SETAC 1991]. Other approaches define four major stages: raw materials acquisition; manufacturing (including materials manufacture, product fabrication, filling/packaging/distribution); use/reuse/maintenance; and recycle/waste management [CSA 1994].

IMPACT ASSESSMENT

The inputs and outputs quantified in the previous stage are linked to their environmental and health impact indicators through classification, characterization, normalization and valuation

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[1] SETAC 1991.

steps. This assessment involves defining categories of potential impacts and assigning particular inventory items to a category (or categories). Methods exist for translating some of the inventory components into numerical impacts during the characterization stage. The impact assessment provides information on generic, potential impacts; the assessment is not intended to provide information on site-specific, actual impacts. Further research is needed in this area before an overall environmental performance can be evaluated [SETAC 1997].

IMPROVEMENT ASSESSMENT

This stage, which is currently being developed, involves identifying areas for improvement once the impact indicators have been identified. Several improvement strategies exist that are based on the concept of sustainable development and system management.

2. LIFE-CYCLE FRAMEWORK (LCF) FOR SITE REMEDIATION OPTIONS

2.1 SUMMARY

To address environmental burdens associated with contaminated sites and issuing from remediation activities, a Life-Cycle Framework (LCF) has been developed based on Life-Cycle Management (LCM) and Life-Cycle Assessment (LCA) methods. The objective of the approach is to broaden consideration of potential environmental impacts beyond the contaminated site and over a prolonged time frame, e.g., to include impacts at sites receiving contaminated soils and from which clean soils are taken, and activities associated with the remediation such as on-site monitoring and maintenance of waste disposal facilities. The LCF outlines a generic approach developed for application to a wide range of remedial options, and consists of a qualitative approach based on LCM, and a more rigorous, quantitative adaptation of the LCA method. This novel application of the LCA method required specifying: a) life-cycle stages appropriate to remediation activities; b) a 25 year time horizon to include long term impacts such as those from contaminants left on-site or at a disposal facility; c) a spatial boundary that encompasses the contaminated site and other locations such as waste disposal facilities; d) a process boundary that contains the contaminated soil; and e) an impact assessment method that considers site- and process-related metrics.

2.2 INTRODUCTION

In this chapter the Life-Cycle Framework for analysis of soil and groundwater remediation options is presented. The framework is based on the life-cycle concept, which promotes scrutiny of soil remediation activities from "cradle-to-grave" and will assist in clarifying potential impacts associated with site remediation options. An outline of the life-cycle approach for site remediation options framework is shown in Figure 2-1, and the major components of this framework are briefly described below.

Life-Cycle Assessment's (LCA) conceptual basis, often termed "life-cycle thinking," involves analyzing and minimizing burdens associated with a product, service or activity over its life cycle. LCA offers a systematic method for evaluating product-based systems, traditionally in the manufacturing and processing sectors [CSA 1994, SETAC 1991, SETAC 1993a,b, SETAC 1992, U.S. EPA 1992]. Taking advantage of LCA's "life-cycle thinking" while simplifying the method, Life-Cycle Management (LCM) has recently evolved as a systematic approach to conceptualize and structure environmental activities, to improve strategic decision making, and often to associate economic efficiency with environmental improvement [Young 1996a, Environment Canada 1995].

Though LCM and LCA approaches have been typically used for product-based systems, these approaches can be modified for new sectors where systematic consideration of environmental and human health burdens over an activity's life cycle is required. For example, LCA has been used to integrate broad environmental considerations into debates of solid waste disposal. In so doing, the adaptation of LCA to waste management practices required appropriate definition of the functional unit and system boundary, and distinguishing classes of environmental burdens [Kirkpatrick 1996, White et al. 1995, EUROPEN 1996, Doig and Clift 1995]. Similarly, Cowell and Clift [1995] describe new issues arising when applying LCA to food production systems.

This chapter discusses a new application of LCM and LCA to contaminated site remediation activities. These activities, though directed towards minimizing short and long term risks posed by contaminants on-site, have inherent burdens that differ according to the technology. In other words, remediation technologies themselves entail impacts. Impacts associated with all options merit consideration so that the ultimate goal of minimizing direct exposure to, and movement of, contaminants, is achieved. Presently, government and corporate policies, which are directed towards protecting public and ecological health by minimizing liability and risks at contaminated sites, focus their attention on the site *per se,* and do not typically consider total risk or environmental effects in a broader geographic and temporal context. Often the choice of remediation options is predominated by financial and/or technical considerations, rather than environmental or health protection.

To fully protect public and ecological health, we should consider whether remediation activities may clean up contaminated sites and reduce risk in the immediate geographical location, while increasing risk at a larger scale and over a longer time. Examining site remediation activities using "life-cycle thinking" allows for a systematic review of impacts

beyond those immediately associated with the contaminated site and, therefore, promotes consideration of potentially wider impacts.

2.2.1 Objectives

The goal of this research is to develop a life-cycle based approach, which we termed Life-Cycle Framework (LCF), to examine the broader environmental and human health implications associated with soil and groundwater remediation. This chapter presents the LCF that includes a description of LCM and a discussion of the modifications required to apply existing LCA methods to site remediation options.

2.2.2 LCF Overview

The Life-Cycle Framework (LCF) was developed specifically for application to contaminated soil and groundwater remediation options. To be of general use, the LCF must accommodate a wide range of remedial options varying in complexity from high technology ex-situ approaches, to in-situ biotechnology, to risk management approaches, and to no-action.

To ensure the LCF's general applicability, the framework offers two approaches of different complexity: (i) the qualitative and comparatively simpler LCM; and (ii) the quantitative and more in-depth LCA. The overall LCF, consisting of the LCM and LCA approaches, is illustrated in Figure 2-1. The LCM approach is based, in part, on existing LCM concepts [Environment Canada 1995, Young 1996a]. LCM could be useful for increasing awareness of life-cycle related issues, identifying potential impacts related to a remedial activity, or investigating implications of resource use. LCA, as applied to contaminated site remediation activities, is based on existing methods [SETAC 1991, SETAC 1993a,b, CSA 1994, U.S. EPA 1992] and necessary modifications are suggested. This approach is useful for more detailed investigation beyond LCM where, for example, quantitative information on resource use, or information on potential impacts, is required.

The overall LCF has two distinct applications: for site remediation design and analysis of remedial activities either completed or underway. Using the LCF "for design" involves choosing the optimal remedial option to minimize environmental and human health burdens in a qualitative sense. The design may consider the types of raw materials used (e.g., nutrients, washing agents), energy and natural resource use, transportation issues, waste management options, and long term impacts of post-remediation activities. A design application requires the use of generic data, models, or estimates of burdens rather than site-specific information, and thus is suitable for use prospectively. The amount of information required for decision-making depends largely on the goal of the study.

When using the LCF "for analysis," a single site or numerous related sites (i.e., contaminated site remediation case studies) may be examined prospectively or retrospectively. The focus of the analysis may be, for example, to increase awareness of the impacts associated with a particular remediation approach or may provide insight into resource use associated with specific remedial options.

Alternatively, LCF "for analysis" may be used to provide insight into current policy focus by prioritizing areas of improvement within policy, or to "build in that extra dimension of having an environmental policy which actually seeks to facilitate improvements relative to a series of environmental concerns" [Kirkpatrick 1996]. Where existing policy may focus on protecting the contaminated site over the recipient of generated waste, insufficiently protecting adjacent communities, or promoting one remedial approach over another due to technological considerations, the policy focus may be inconsistent with minimizing environmental and health burdens in a broader context. Since the environmental and health impacts of a particular method are often site-specific, we do not expect that this method will provide absolute statements of impacts associated with a particular option. Rather, LCF "for analysis" can produce insight into the existing environmental policy, the decisions that may be taken, and the potential impacts or burdens associated with specific activities. As such, the analysis can provide guidance for subsequent decisions on site clean-up activities.

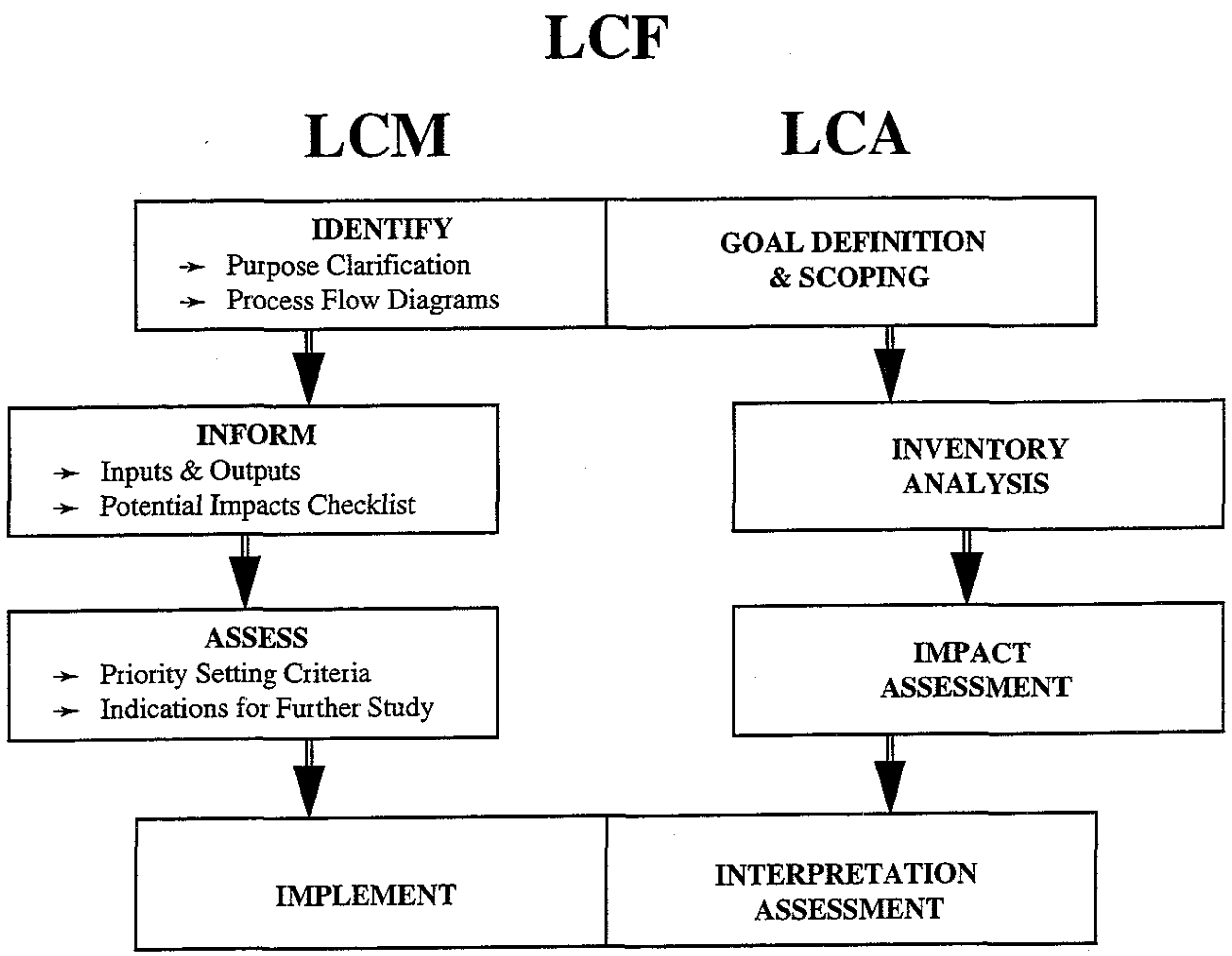

Figure 2-1 Components of the Life-Cycle Framework for assessment of contaminated site remediation options

2.3 *LCM FOR SITE REMEDIATION*

2.3.1 Introduction

LCM for investigating contaminated site remediation activities consists of four components: *Identify*; *Inform*; *Assess*; and *Implement*. *Identify* involves clarifying the purpose of the study and describing the remedial system through process flow diagrams. *Inform* involves determining the inputs and outputs into the remedial system, and investigating the associated potential impacts. Priorities are clarified in *Assess*, and consideration of, and direction to, future study is made. *Implement* involves acting on the study's conclusions and may be made in conjunction with any other LCM component. Descriptions of each LCM component are given below.

IDENTIFY

The purpose of this first step is to understand the remedial option under consideration. This step includes clarifying the purpose of the investigation, describing the remedial system, and developing the process flow diagram. The remedial option is characterized so that it can be readily understood and further broken down into life-cycle steps.

INFORM

In this step, information about the inventory is gathered for the process under consideration. The inputs and outputs of the remedial system and other important factors are determined. This step helps to identify data limitations and problems in understanding the system. It may involve speaking with consultants, contractors, remediation experts, or suppliers to improve the understanding of the remedial process. This step should include the completion of a Potential Impact Indicator Checklist. To go beyond the checklist approach, the potential impact indicators may be ranked according to appropriate predetermined priorities.

ASSESS

Based on the understanding of the system gained by employing steps I and II, the situation may be assessed. This assessment depends on the purpose of the study and, consequently, the level of detail required to meet the objectives. The Priority Setting Criteria are a useful guide. Adequate progress may be made using the LCM, or the more rigorous Life-Cycle Assessment tool may be applied.

IMPLEMENT

Implementing the decisions made in the assessment, in line with the study's purpose and the priority criteria, depends on the user's priorities. Implementing the LCM results may ultimately involve choosing a different supplier for raw materials, devising methods to conserve energy, recycling streams of water, or even choosing another remedial approach entirely.

2.3.2 Identify

PURPOSE CLARIFICATION

As a first step, the purpose of using LCM to examine a remedial option is described (Purpose Clarification). LCM can be used for design or analysis of site remediation options, prospectively or retrospectively, and can be applied at any level of detail either site-specifically or generically.

Clarifying the purpose at the onset maintains a focused study and helps to determine the extent of information or assessment required. Guiding questions to consider when first applying the LCF or LCM are given in Table 2-1 below.

Table 2-1 Guiding questions to consider when first applying the LCF

Areas	*Questions*
Application	• Will the LCF be used for analysis of a remediation option (e.g., case study) or to design a remedial approach?
Assessment Goals	• What are the main goals: to better understand the existing system; to determine opportunities for improving the existing system; to compare remedial systems and their potential impacts; or, to select a remediation option prospectively?
End Users	• Who is (are) the audience(s) for this study? • Will the assessment be used within a private company or publicly? (this choice influences the degree of accountability, whether open to review, level of transparency, etc.)
Bounding the Remediation Option	• What are the temporal, geographic and process boundaries of the remediation option or activity? • What processes are secondary or will be neglected?

PROCESS FLOW DIAGRAMS AND LIFE-CYCLE STAGES

The development of process flow diagrams aid in understanding the remedial option being considered. An example of a generic flow diagram is given in Figure 2-2. When describing the remedial option, the processes involved are usually broken down into functional units in an attempt to outline all activities from cradle (i.e., pre-processed source) to grave (i.e., disposed of with no future use).

The major stages of life-cycle inventory, as described in *A Technical Framework for Life-Cycle Assessment* by SETAC [1991] and *Product Life-Cycle Assessment: Inventory Guidelines and Principles* by the U.S. EPA [1992], include the following: raw materials acquisition and energy; processing or manufacturing; distribution and transportation; use/re-use/maintenance; and recycle/waste management. The importance of following LCA convention by breaking down a process into the above stages is most apparent when trying to avoid duplicating or omitting aspects of the process under consideration.

Box 1

LIFE-CYCLE STAGES
- raw materials and energy acquisition
- site processing
- post-site processing

LIFE-CYCLE SUB-STAGES
- transportation and distribution
- waste management
- monitoring

The unit processes, as identified in the Process Flow Diagrams, are now grouped according to life-cycle stages appropriate to site remediation options. These stages are given in Box 1 above. Life-cycle sub-stages, that may be associated with any life-cycle stage(s), include transportation and distribution, waste management, and monitoring. Descriptions of the life-cycle stages are given in Table 2-2 below. Note that waste management refers to dealing with wastes generated from remediation activities, not the contaminated soil or groundwater. At times, the distinction may not be entirely clear, e.g., contaminants remaining on-site versus a contaminant concentrate from soil washing versus contaminants discarded in landfill as solid waste. The actual category is not important, only that all possibilities are included and are reported.

Table 2-2 Life-cycle stages and sub-stages for contaminated site remediation options

Life-Cycle Stage	*Description*
raw materials and energy acquisition	• activities surrounding the acquisition of raw materials (e.g., primary or secondary) and materials used or consumed in maintaining the raw material source.
site processing	• the actual treatment of the contaminated soil and groundwater, and is considered complete when the contaminated soil and groundwater have been treated. Because of the disparity between remediation technology effectiveness, treated soil and groundwater signifies only that it has been exposed to a remedial option (i.e., does not relate to contaminant concentration or degree of "clean").
post-site processing	• activities occurring after site processing while still falling within the overall life-cycle span (e.g., activities to maintain site security, upgrading of capping or barrier walls, collection of leachate or migration control).
Life-Cycle Sub-Stage	*Description*
transportation and distribution	• changing the location of the soil, groundwater and materials used as inputs (e.g., reagents, clean fill) and outputs (e.g., waste concentrates). Transportation involves moving materials or energy, whereas distribution encompasses all non-transportation activities that facilitate the transfer of the soil, groundwater and other materials (e.g., stockpiling, warehousing).
waste management	• techniques used to treat, handle or contain a waste prior to its release into the environment, and relates to all LC stages. Waste is considered an output, with no market value or intrinsic use, discharged into the environment through air, water, and/or land [CSA 1994]. Waste may be released under routine and accidental conditions. Important considerations include the categories of waste (e.g., non-hazardous, hazardous), and receiving medium. Emission control systems fall under this sub-stage.
monitoring	• relates to all life-cycle stages and may involve the surveying and tracking of emissions from all activities. Monitoring activities may be conducted for any remedial option, and do not include measures for emission control (included under waste management).

The life span of the remediation option continues beyond completion of site processing to encompass all related activities associated with the remediation. We suggest a life span long enough to account for long term impacts, such as activities associated with partially de-contaminated sites or waste management (e.g., maintaining a hazardous landfill site).

Once the life-cycle stages are determined, the major unit processes within each life-cycle stage are identified, and the overall process flow chart is refined. Figure 2-3 illustrates a simplified soil washing remediation process showing life-cycle stages and unit processes.

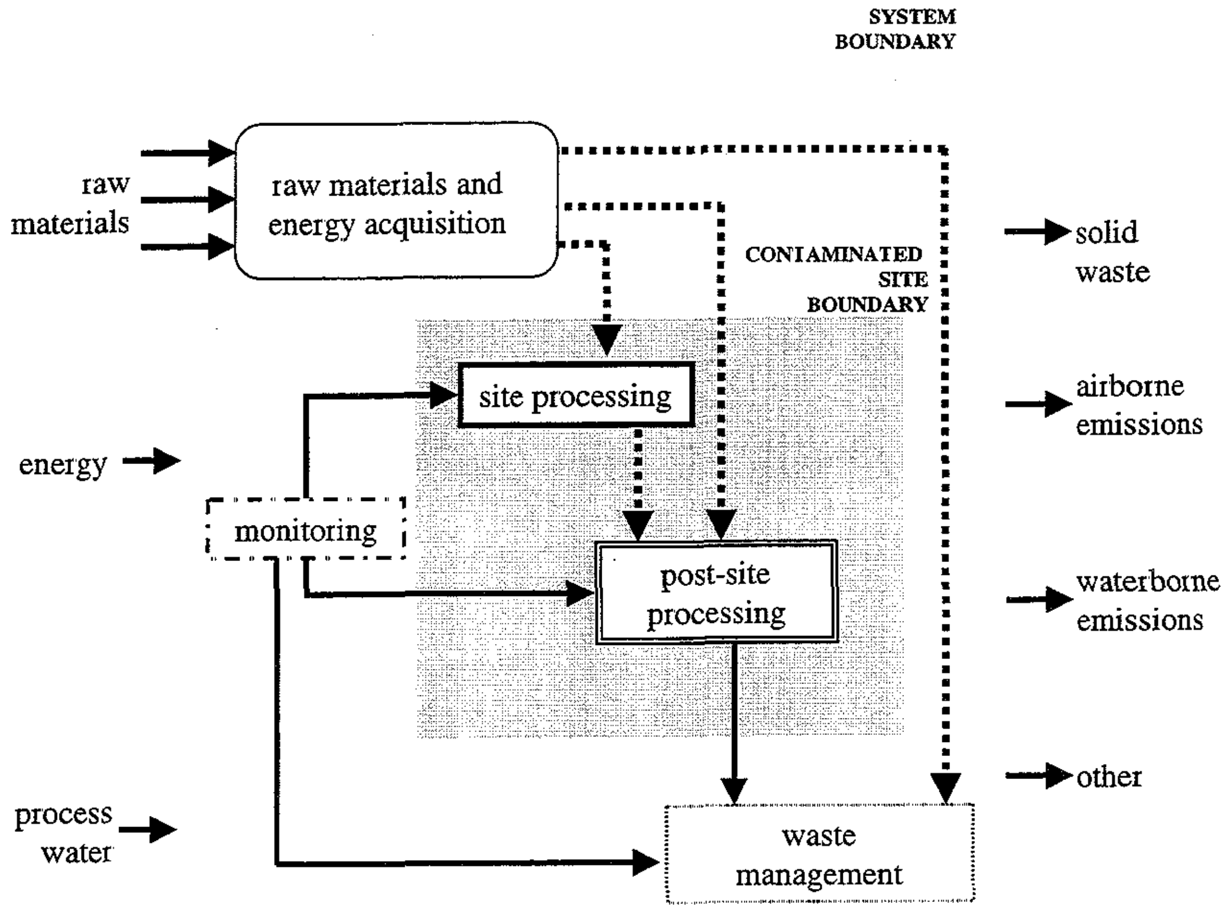

Figure 2-2 Simplified generic remedial option according to life-cycle stages

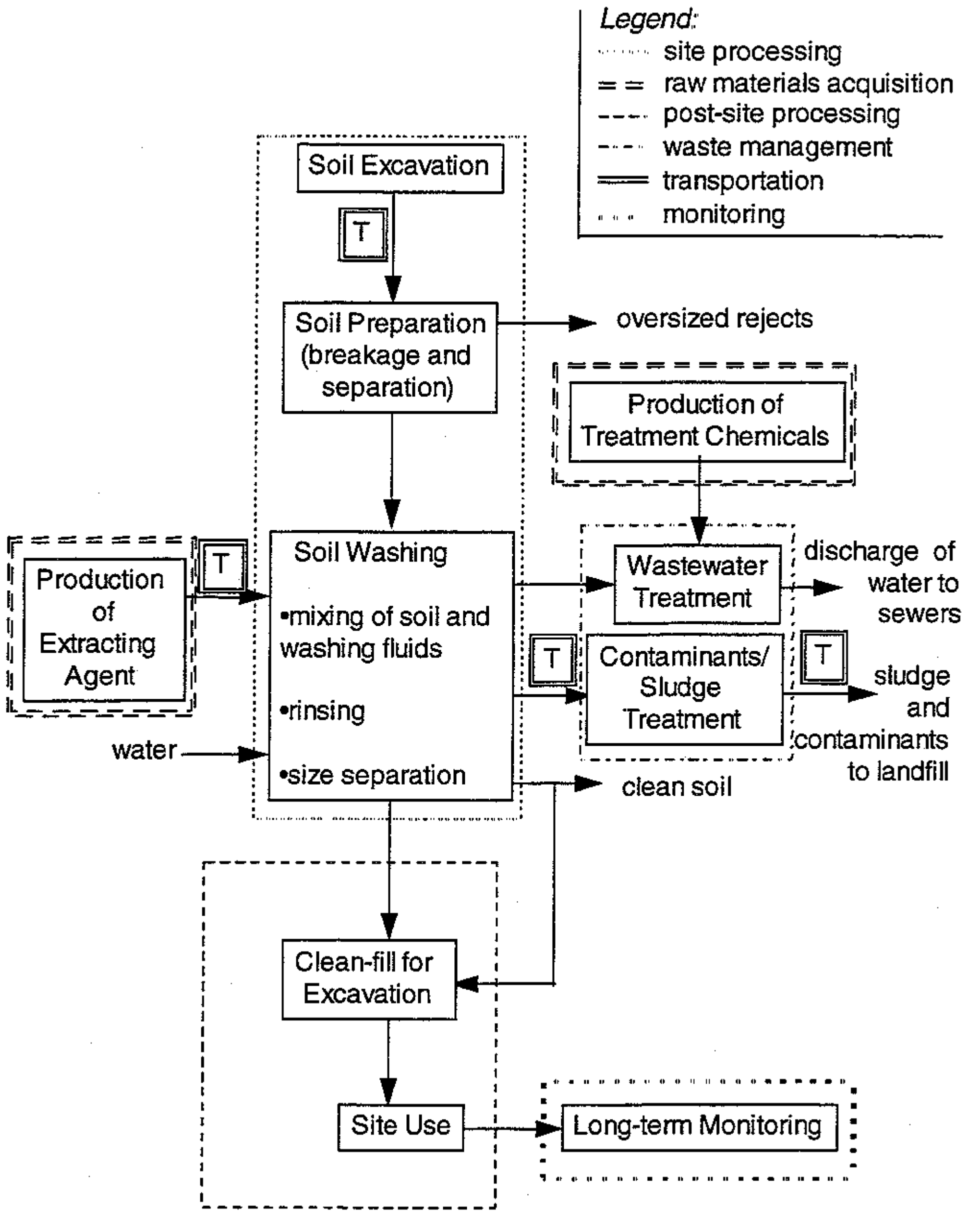

Figure 2-3 Simplified soil washing remedial option according to life-cycle stages and major unit processes

2.3.3 Inform

Once the life-cycle stages have been determined and the unit processes identified, the inventory of inputs and outputs is compiled based on the flow charts. Depending on the purpose of the study, the inventory information gathered may be qualitative, or quantitative. Table 2-3 lists categories of inventory items. When considering contaminated site remediation activities, inventory information gathered includes measurements, estimates or averaged values, and non-traditional items. For example, information on land use (e.g., consumption of space), or land associated with ecosystem and landscape degradation must be noted. In addition, appropriate measures (e.g., area) or information (e.g., location of habitats, impervious surfaces, land fragmentation, land stagnation) should be gathered. For clarity of subsequent analysis, a data compilation tool, as given in Figure 2-4 and Figure 2-5, is often useful when systematically recording inventory information [SETAC 1994, CSA 1994]. Note that the data compilation tool given here, in addition to accommodating numerical inventory items, allows for collection of information on resource depletion, ecosystem impact, and human health effects.

Table 2-3 List of typical inventory item categories associated with contaminated site remediation options

Inputs	*Outputs*	*Other Items*
• untreated soil	• treated soil (e.g., soil quality, contaminant levels)	• associated with physical ecosystem degradation
• materials (e.g., process)	• air emissions (process release and fugitive)	• associated with landscape degradation
• water	• solid waste	• associated with disturbances to humans (e.g., noise, odour, vibration)
• energy (process and transportation)	• water effluent • heat discharge	

A raw materials or emissions database appropriate for site remediation activities is currently not available. Therefore, using LCM for design may require acquiring information from contractors, suppliers or consultants directly involved with site remediation. If considering a case study, information may be derived from many sources, however, the type and extent of data required for a life-cycle inventory are not routinely gathered or available, e.g., fugitive emissions are difficult to determine but may be estimated. Thus, data gaps are endemic to case studies.

Remedial Option:	*Unit Process:*	*Date:*

INPUTS

	Main and Supplementary Material Inputs	Energy	Water
Descriptions			

Unit Process Description

OUTPUTS

	Air Emissions	Water Effluents	Solid and Liquid Wastes	Marketable Products
Descriptions				

Figure 2-4 Compilation tool for site remediation activities (first page)

Distribution/Transportation Modes	
Possible Resource Depletion/ Land Disturbances	
Possible Human Health Effects/Impacts	
Possible Ecosystem Impacts	
Notes/References	

Figure 2-5 Compilation tool for site remediation options (second page)

POTENTIAL IMPACTS CHECKLIST

Assessing impacts, the next stage, involves linking inventory items, or groups of inventory items, with potential environmental impacts. Applying LCM at its simplest level involves identifying potential impacts, associated with all stages of the remedial option under consideration, using a "Potential Impacts Checklist". The purposes of the checklist are to raise concerns and ensure that potential impacts associated with any life-cycle stage are neither overlooked nor ruled out.

The Potential Impacts Checklist (Table 2-4), gives potential impacts associated with stressors. Stressors are physical, chemical or biological conditions or entities that can induce positive or negative impacts on the environment, humans, or resources [CSA 1994]. Each stressor, or group of stressors, is associated with one or more potential impacts. These impacts represent a wide range of generic, rather than site-specific concerns. Thus, this impact assessment is not comparable to, or intended as, risk assessment which is widely used in the site remediation arena (e.g., to establish clean-up levels) [MOEE 1996, U.S. EPA 1989].

To help conceptually organize the inventory information, the stressors and their associated potential impacts are grouped in three categories: pollution, depletion, and disturbance [Guinée et al. 1993]. "Pollution" relates to all types of emissions to the environment; "depletion" includes inputs, or extraction, from the environment; and "disturbance" reflects human social impacts and structural changes within the environment. For land issues, stressors and potential impacts are classified under "disturbances", and include physical ecosystem and landscape degradation (i.e., habitat fragmentation). Solid waste and the associated land consumption impacts, however, are considered under "depletion" since the concern is about removing land for "useful" purposes such as for habitat. Other LCA guidelines categorize potential impacts and stressors differently, using the four broad stressor categories, ecosystem health, human health, resource depletion, and social health [CSA 1994, SETAC 1993a]. We have chosen to categorize potential impacts as above to create a simplified and non-anthropocentric approach. The assigning of "Levels of Concern" relies on a multi-stakeholder group to minimize bias and distortion when approximating the relative importance of the various stressors for the defined situation.

Table 2-4 Potential Impacts Checklist

Stressors	*Potential Impacts*	*Priority/Level of Concern*		
		Low	Medium	High
Pollution				
• acid emissions (e.g., SO_2, HCl, NO_x, particulates)	→ acid rain			
• greenhouse gases (e.g., CO_2, CFCs, methane, methyl chloride)	→ global warming			
• ozone precursors (e.g., CFCs, CO, methyl furan, methyl chloride)	→ ozone depletion			
• photochemical fog precursors and air polluters (e.g., VOCs, semi-volatile compound, PAHs, NO_x, SO_x, particulates)	→ air pollution			
• nutrients (C, N, P)	→ eutrophication			
• chemical changes to water quality (e.g., TSS)	→ stress on aquatic species			
• chemical changes to soil quality (e.g., nutrient levels, organic content, pH)	→ soil quality disturbances			
• toxic compounds in ground and surface water	→ groundwater impacts (ecotoxicity) → human health impairment (toxic effects)			
• toxic compounds in soil	→ soil impacts (ecotoxicity) → human health impairment (toxic effects)			
• toxic compounds and particulates in air	→ airborne transport to other media (ecotoxicity) → human health impairment (toxic effects)			
Disturbance				
• heat discharge	→ heat damage/dispersion of heat			
• land fragmentation	→ habitat alteration			
• non-remediation of land	→ land stagnation			
• construction, excavation	→ habitat destruction/ alteration			
• compaction, paving, or application of an impervious soil coverage	→ effects on soil moisture, aquifer recharge, ecosystem regeneration			
• changes to water quantity in aquifer	→ interrupted drainage, changes in aquifer level, change in stream base flow			
• non-chemical soil quality changes (e.g., heating effects, soil particle size)	→ soil quality disturbances			
• human social stressors (e.g., noise, dust, odour, vibration, aesthetic value, process heat)	→ human social disturbances			
Depletion				
• fossil fuel use/energy consumption	→ primary energy source depletion			
• solid waste	→ land or space consumption			
• water use	→ water consumption			
• mineral use	→ mineral consumption			

Approaches similar to the Potential Impacts Checklist, used in LCA, include the Checklist Approach and the Relative Magnitude Approach [RTI 1994]. The Checklist Approach involves a classification matrix to provide a qualitative survey of inventory items and impact correlations. For the Relative Magnitude Approach, within impact categories, inventory items are grouped based on amount (quantity or volume) to indicate relative contributions to specific burdens. We have suggested ranking stressors according to level of concern rather than amounts since the latter can be misleading when dealing with chemical and non-chemical contaminants of varying potency, and not all stressors lend themselves well to an approach based on amounts. The approach recommended here, of ranking according to level of concern, was used by Campbell et al. [1995] to assess the potential environmental and health impacts related to site remediation technologies.

2.3.4 Assess

PRIORITY SETTING CRITERIA

Once the remedial system is analyzed through the *Identify* and *Inform* components, the information gathered is assessed and future study is considered. This assessment depends on the purpose of the study and, consequently, affects the level of detail required to meet the objectives. Determining the necessity of future work on an inventory item or process can be inferred from the "Levels of Concern" in Table 2-4, in conjunction with the following decision points and related questions (Table 2-5).

Table 2-5 Decision points for future investigation of site remediation options

Indications for Further Study	*Questions to Consider*
Consumption Levels	• How much of the inventory item is used? The "less is best" principle may apply.
Toxicity Levels	• Is the inventory item considered toxic, persistent or bioaccumulative? How much of the inventory item is used or emitted in the activity?
Liability	• How hazardous is the inventory item to human or ecosystem health? Is this item regulated?
Environmental Sensitivity	• Is the inventory item considered environmentally sensitive? If a disturbance, is the disturbance in an environmentally sensitive or valuable area? Is a sensitive species, population or community disturbed? How geographically broad or long term are the effects?
Associated Costs/Opportunities	• What are the costs associated with attempting to alter (e.g., decrease amount produced) versus not changing the inventory item?

INDICATIONS FOR FURTHER STUDY

Once the decision points have been considered, key areas for improvement are identified and further study may or may not be pursued. At the simplest level, the LCM approach provides an increased awareness through life-cycle thinking as applied to site remediation, or a cursory investigation into potential impacts associated with a remediation technology. The LCA approach should be used for more detailed study if, for example, a stressor is highly toxic or has an important associated environmental, human health or resource burden, or if clarification of impacts or greater consideration of key resources or raw materials is necessary. The LCA approach should also be used for a more systematic, rigorous and detailed assessment of site remediation options.

2.3.5 Implement

The underlying purpose of LCM is to minimize the burdens associated with the site remediation options under analysis. Once the decision points have been considered, key areas for improvement are identified. At the simplest level, the LCM approach provides awareness through life-cycle thinking and a cursory investigation of potential impacts associated with a remediation technology. At a higher level, LCM helps to identify key areas for improvement that are consistent with the study's purpose and depend largely on the user's priorities. Therefore, areas for improvement may be identified from a simple LCM study, or in the early stages of a LCM analysis, e.g., opportunities for energy conservation or possibilities for reducing transportation-related burdens.

2.4 LCA FOR SITE REMEDIATION

2.4.1 Purpose

The LCA approach is useful for systematic, rigorous and detailed assessment of site remediation options. Used in the manufacturing or processing sectors, the LCA method has been developed for, and has mainly focused on, the analysis of a product or process. Modifications are necessary, as previously discussed, when applying LCA to other uses such as solid waste management or food production systems, and in this case, site remediation.

2.4.2 Boundaries

The quality of a life-cycle inventory, and the subsequent life-cycle impact assessment, is dependent on an accurate description of the system under analysis. To describe the system, boundaries are defined. The term "boundary" refers to geography and time, and also the inclusion or exclusion of specific stages, sub-stages, or processes. Establishing system, temporal, and geographic boundaries is critical to the overall objective of expanding environmental and health concerns beyond the boundary of the contaminated site.

In defining process or system boundaries, it is important to include all steps that could affect the overall results, interpretation of results, or the ability of the analysis to address the purpose of the study. Resource constraints for the life-cycle inventory may be a consideration in defining the system boundaries, however, the scientific basis of the study should not be compromised. The ultimate criterion, on whether the boundaries and end points adopted are acceptable, is the environmental significance of the exclusions to the LCA.

SYSTEM BOUNDARY

The system includes all operations involved in the remediation of the contaminated soil and groundwater, and the system boundary separates the system from the surrounding environment. A boundary issue arising when applying LCA to site remediation options is whether soil should be included within the system boundary. For options involving soil excavation followed by treatment (e.g., soil washing), soil and groundwater might be considered outside the system. However, if the treatment option leaves the soil structure intact (e.g., in-situ bioremediation, soil venting), then the soil may be regarded as inside the system boundary. We propose that, because the soil is an integral component of site remediation processes, it should be included within the system boundary. Similarly, Cowell and Clift [1995] recommended that soil be included within the farming and food production system of an LCA of food production, and emphasized that changes in soil quality should form part of the inventory analysis. Likewise, we propose that including soil within the system necessitates consideration of "site quality". Site quality is addressed through Impact Assessment using a suite of site quality metrics discussed below, and involves additional metrics to those pertaining to process-related activities.

TEMPORAL BOUNDARY

The temporal boundary must encompass the time taken for all remediation activities and over which concern arises. In order to do this, the length of the life cycle of the site remediation processes under consideration must be established. Secondly, the temporal boundary influences the age of data used in the inventory stage.

For studies of site remediation, the life cycle begins when the actual site remediation commences. The various remediation processes, however, have life cycles of different duration. When comparing various processes, a time horizon must be chosen to encompass all the processes under consideration. We propose to use a time horizon of approximately 25 years. The extended time frame is necessary so that the LCA does not prejudice options that may have high impacts over a short time relative to other options (e.g., no-action) that may have low impacts over a long time. The 25-year time frame has been arbitrarily selected to encompass most technologies. Data should be estimated and projected over this time period which, we acknowledge, can be problematic, since the processes considered are unsteady-state (i.e., vary with time). Thus, non-linear methods to project inputs, outputs and impacts should be used.

GEOGRAPHIC BOUNDARY

The geographic boundary is central to the original intent of using a LCA approach for site remediation. It allows for consideration of activities at and beyond the contaminated site itself. Thus, LCA can consider geographic shifts of burden from one site to another, e.g., where excavation and disposal involves relocating contaminated soil to another geographic area and clean fill must be transported from yet another location.

2.4.3 Functional Unit

The *functional unit*, or normalizing factor, is a performance measure necessary for comparative studies, that should reflect the total benefit or service provided by the system, the product lifetime, the study objectives, and the equality of products produced (e.g., quality and quantity) [SETAC 1993b]. For site remediation, the primary process is treating contaminated groundwater and soil, and the benefit or service provided is the remediation of a contaminated site. The function provided is the remediation of the site that, depending on the technology used, can result in a wide range of final on-site contaminant concentrations, and vary in effectiveness or permanence of remediation. For example, a technology may immobilize metals but not treat organic contaminants, whereas another contains rather than treats contaminants.

A functional unit that conveys "equal use utility" would be best, however it is difficult to develop such a unit given the wide variety of remediation outcomes and dependence of land use potential on social and/or economic factors (e.g., land value depends on location, market conditions, etc.). Although a single best functional unit is unclear, we suggest that the functional unit should relate to the production of an equivalent amount of treated soil and groundwater; we consider site quality separately. The amount of treated soil, expressed as a volume or mass, is most readily quantified when the site is characterized initially. More accurate estimates of final volume or mass would be obtained for options involving soil excavation, however, these values are likely to be uncertain for in-situ treatment or containment options, or for the no-action scenario.

Since mass or volume of cleaned soil do not address the extent of clean-up, contaminant immobilization nor the quality of the treated soil, site-related impact metrics are suggested to address the nature of clean-up. These metrics include the concentrations of contaminants in soil and groundwater, pH, porosity, particle size distribution, organic matter content, nutrient content, and ion exchange capacity. Other metrics that reflect the final nature of the site should also be included (see Section 2.5).

2.4.4 System Flow Diagram

A flow diagram of the process under consideration facilitates analysis. The main process flow is first identified, and ancillary material flows are then added. The system may be described as shown previously in Figure 2-2. Due to the nature of remedial options, which may range from no-action to complicated, multi-stage remedial technologies, the generic model must necessarily be a simple system that can be adapted.

2.4.5 Data Issues

The results of any LCA are contingent on the data used. As outlined by SETAC [1994], many data types and sources exist, and several data categories can be considered. Specific data issues arise when applying LCA to site remediation options, whether for design or analysis. When LCA is used for analysis of remedial options, case studies are usually considered and, consequently,

data are obtained from primary sources. Most data collection for site analysis occurs over the duration of the actual site remediation, and the data sources are facility-specific industry or consultants' reports that are generally considered proprietary information. The data available are usually individual observations and measurements, though emissions and long term monitoring data are routinely averaged and reported on a monthly or weekly basis. The data, being specific to particular remediation cases, are not representative of the site remediation industry, and deviations or variations are not smoothed out. Data from government documents and environmental assessments typically lack sufficient detail and were collected for purposes other than LCA. Since consultants, suppliers, contractors, and technology vendors offer judgmental data, caution must be exercised with these data. Ideally, data should come from an unbiased source and be subject to review. When using LCA for design, problems arise in accessing generic data. Models for predicting LC inventory data do not exist; likewise, generic databases specifically for site remediation are not yet available.

SOURCES

This study was designed to develop a framework to be applied to remediated site case studies and, consequently, the data are often obtained from primary sources. These data sources are facility-specific industrial data and are, for the majority, not publicly accessible. In terms of geographic specificity, the scope of interest is often regional as opposed to national or international.

DATA AVAILABILITY SURVEY

Once the flow diagram of the remediation system under analysis is drawn, the inputs and outputs for each main process are identified. All ancillary materials used in the process are indicated. Energy sources associated with process equipment and on-site transportation activities are listed. Data sources, types and omissions are indicated for all inputs and outputs.

For each unit process, boundaries are delineated, including a description of operations and the state of raw materials as they enter the process. Data for the following should be identified: water use; water source, e.g., from ground or surface; air emissions including actual discharges and fugitive emissions; water effluents; and solid waste.

DECISION RULES

Decision rules, based on an evaluation of energy, mass and environmental significance, may be applied when considering the exclusion of ancillary materials. These data would come from the data availability survey.

Total mass may be estimated from inputs recorded during preliminary data collection and initial main process flow mass balances. Then a percentage of total mass input may be calculated. To determine process boundaries, we use the decision rule developed by the CSA [1994]:

> An appropriate decision rule would be to require the inclusion of all raw materials that have a cumulative total of more than a fixed percentage of the total mass in the system....It is recommended though that the cumulative total based on mass contribution be greater than 90%.

Some ancillary materials are very energy intensive. Thus, decision rules must also be established for energy consumption and environmental relevance. Information on environmental releases that could adversely impact the environment should be investigated using expert advice or literature.

DATA QUALITY

As discussed in SETAC's *Life-Cycle Assessment Data Quality: A Conceptual Framework* [1994], it is important to have data quality information relating to data sources, data categories, levels of aggregation and generation processes. The data quality information is listed below.

A. *Data Sources*
  1. industry reports
  2. laboratory test data
  3. government documents
  4. journals, books, patents
  5. reference books
  6. data bases
  7. industry consultants
  8. related LCIs/LCAs

B. *Data Categories*
  1. individual data
  2. aggregated data
  3. historical data
  4. modelled data
  5. encountered data
  6. judgmental data

C. *Level of Aggregation*
  1. individual observations
  2. averages (monthly, annual)
  3. normalized (per unit values)

D. *Generation Process*
  1. actual measured
  2. estimated/sampled
  3. modelled/calculated
  4. regulated

PEER REVIEW

In accordance with the recommendation of SETAC [1991] and CSA [1994], this research has been subject to peer review at critical points in the project. The reviews assessed the validity of the project's scope and boundaries method, and critiqued the data compiled and estimated in the inventory stage. The key assumptions, results and conclusions drawn were also reviewed.

2.4.6 Life-Cycle Stages

According to traditional LCA inventory methods, the major life-cycle stages include: raw material and energy acquisition; manufacturing or processing (including materials manufacture and product fabrication); distribution and transportation; use/re-use/maintenance; and recycling and waste management [SETAC 1991, U.S. EPA 1992, CSA 1994]. The intention of the LCA convention, of breaking down a process into these stages, is to avoid duplication or omission of any activities. For LCA as applied to site remediation, the modified stages are: raw materials and energy acquisition; site processing; post-site processing; transportation and distribution; waste management; and monitoring (as previously defined in Table 2-2). While some stages are not encountered for all remedial options, the stages accommodate most scenarios. More detailed descriptions of the life-cycle stages are given below.

RAW MATERIALS AND ENERGY ACQUISITION

This stage includes all activities surrounding the acquisition of raw materials (e.g., primary or secondary) and materials used or consumed in maintaining the raw material source. The raw materials depend upon the remedial option (e.g., clean fill, chemical reagents). The energy sources are identified, pre-combustion quantities (e.g., weights, volumes and energy content) are determined, and geographic sources of the energy are established. Air emissions, water effluent, solid waste, energy and other environmental releases are also determined for this stage. Handling and transportation steps within the system may prepare or deliver the raw material, but do not alter the raw material.

SITE PROCESSING

The site processing stage (i.e., the renamed "processing or manufacturing" stage) involves the "treatment" of contaminated soil and groundwater, and is considered complete when the contaminated soil and groundwater have been "treated" (i.e., been exposed to a remedial option). Inputs include energy and raw materials (including water) while outputs include emissions (i.e., solid waste, airborne emissions, waterborne emissions). On-site waste transformation may occur. For example, waterborne organic wastes may be transformed completely into carbon dioxide and water in biological systems, and compounds often undergo physical and abiotic transformations in most other systems. Only the final emissions following transformation are recorded.

POST-SITE PROCESSING

This stage deals with the final activities involved in site remediation. These activities occur after the main activities have ceased, but still fall within the overall life-cycle span (e.g., activities to maintain site security, upgrading of capping or barrier walls, collection of leachate or migration control).

WASTE MANAGEMENT

The waste management stage consists of techniques used to treat or handle a waste prior to its release into the environment, and relates to all stages within the life-cycle inventory, but does not refer to treatment of contaminated soil. Waste is an output, with no market value or intrinsic use, discharged into the environment through air, water, and/or land [CSA 1994]. Waste may be released under routine and accidental conditions. Boundaries of the waste management system must be drawn carefully to begin where the waste is generated and end where waste residuals are discarded or emitted. Important considerations include the categories of waste (e.g., non-hazardous, hazardous), receiving medium, and water and air emissions.

TRANSPORTATION AND DISTRIBUTION

This stage involves changing the location or physical configuration of the soil, groundwater and other materials. Transportation involves moving materials or energy, whereas distribution encompasses all non-transportation activities that facilitate the transfer of the soil, groundwater and other materials (e.g., stockpiling, warehousing). Transportation parameters of interest include mode of transport, energy consumption, environmental control, emissions and distance travelled.

It is important to note that the transportation and distribution stage is closely tied to other aspects of the whole system under consideration. The boundaries of many transportation activities may be defined by the activities that they connect (e.g., on-site or off-site transportation).

Boundary conditions for this stage must be clearly defined. At the simplest level a highway transportation system might encompass only trucks [SETAC 1991]. At higher levels of complexity, this system may include roadways, truck stops, and the maintenance and building of the truck. In our assessment, we adopt the simpler level of analysis so that the research is tractable.

Once the boundaries are established, the input items may be identified. Materials and energy for transportation by truck may include fuel, motor oil, and spare parts. On-site distribution may include electricity, natural gas, product, packing supplies, and cleaning supplies. Outputs are specific to the process and boundaries specified. For transportation by truck, outputs may include air pollutants. For on-site distribution, outputs may include heat loss, emissions, pollutants, product, wastewater, and discarded packaging material.

MONITORING

The monitoring stage relates to all stages of the life-cycle inventory and may involve the surveying and tracking of emissions from all activities. Monitoring activities may be conducted for any remedial option, and do not include measures for waste management emission control.

2.5 IMPACT ASSESSMENT APPROACHES FOR CONTAMINATED SITE REMEDIATION

The objective of Life-Cycle Impact Assessment (LCIA) is to translate inventory items into environmental and human health impacts, thereby giving inventory items a context or environmental significance (Section 1.5.2). It is clear that LCIA provides information on relative and generic, but not absolute nor site-specific, impacts, on the basis of the functional unit [SETAC 1997].

In LCIA, impacts to ecosystems, human health and natural resources are classified and characterized qualitatively and quantitatively. Similarly to LCM, the impact assessment component of LCA requires identification of stressors and potential impacts that are classified within the three impact categories. Unlike LCM, LCA involves translating inventory items into relevant indicators of potential environmental and health impacts using models or assessment approaches. Indicators or metrics aid in quantifying impacts and reflect generic, rather than site-specific impacts. Quantification is predominantly developmental, since few established quantitative impact models exist (e.g., global warming potential, ozone depletion).

Ultimately, site remediation is directed towards protecting public and ecological health by minimizing impacts potentially associated with toxic compounds in the soil and groundwater. Consequently, metrics are necessary to gauge whether remediation mitigates these potential impacts. For LCIA of site remediation activities, we have suggested two sets of metrics for impact assessment: for process-related activities and site-related quality.

2.5.1 Classification of Impacts for Remedial Options

After the inventory component of LCA is developed, the inventory data are assigned to primary impact categories and aggregated into groupings of impacts. The main categories of potential impacts considered include:

- chemical impacts (pollution) to ecosystems;

- non-chemical impacts (disturbances) to ecosystems;
- chemical impacts (pollution) to human health;
- impacts (depletion) to stock and flow natural resources; and
- social impacts.

Table 2-6 to 2-9 give examples of inventory items/stressors that may lead to potential impacts to the ecosystem, human health and natural resources. Social welfare is an additional impact category, but is beyond the scope of this study. For this project, the potential impacts reflect generic impacts, rather than site-specific assessments. Thus, the impact assessment is not comparable or intended to be comparable to a risk assessment.

Table 2-6 includes major chemical stressors, or pollutants, to the ecosystem. The specific inventory items are placed in appropriate stressor categories. For example, carbon dioxide and methane inventory items are placed under the chemical stressor category of greenhouse (or climate change) gases. Note that only the initial impact to the ecosystem is specified and secondary impacts (e.g., climate change leading to changes in biodiversity) are not included at this point. The toxic compounds (i.e., stressors) discharged to groundwater and soil are unique for each site under analysis. The compounds' properties dictate the initial impacts to the ecosystem.

Non-chemical stressors or disturbances to the ecosystem are given in Table 2-7 with their potential impacts. Land fragmentation leading to habitat alteration is included in this section whereas land use is not since it is regarded as a non-renewable (stock) resource and hence is assessed through resource impacts. Heat discharged is described by the amount and intensity of heat emitted at specific locations and can be measured in megajoules (MJ). Ambient temperatures in the area of release must be known. Heat discharged to soil may produce adverse effects to indigenous organisms. The application of impervious surfaces, often used in management approaches, will affect soil moisture and aquifer discharge.

Pragmatically, the inventory items and hence impact calculations will be limited by data availability (e.g. chemicals monitored in landfill leachate, emission factors for vehicles). However, the absence of critical stressors may influence the final outcome of the LCA.

Table 2-6 Sample chemical stressors (Pollution) and their contribution to potential ecosystem impacts

Chemical Inventory Item/Stressor	*Initial Impact to Ecosystem*
♦ acid emissions • SO_2 • HCl • NO_x • particulates	♦ acid rain
♦ greenhouse gases • CO_2 • CFCs • methane • methyl chloride	♦ global warming
♦ ozone depleters • CFCs • CO • methyl furan • methyl chloride	♦ ozone depletion
♦ air polluters and photochemical smog precursors • VOCs • SOC (semi-volatile organic compounds) • PAH • NO_x • particulates	♦ smog
♦ nutrients • C • N • P	♦ eutrophication
♦ toxic compounds to groundwater	♦ groundwater impacts (ecotoxicity)
♦ toxic compounds to soil (e.g., compounds listed in decommissioning guidelines)	♦ soil impacts (ecotoxicity)

Stressors to human health include chemical toxicity, high energy radiation, conditions that promote the potential for accidents, mortality or morbidity due to pathogenic organisms, and food or water deprivation. Due to the nature of this project, the potential human health impacts considered relate only to chemical toxicity arising from exposure to chemical products or wastes entering the environment. Chronic effects to consider may include carcinogenicity, teratogenicity, mutagenicity, neurotoxicity, blood and dermal impacts, reproductive impairment, and major organ impact (heart, lung, liver, kidneys). Consideration of specific impacts depends on the availability of toxicological data.

Table 2-7 Sample non-chemical stressors (Disturbance) and their contribution to potential ecosystem impacts

Non-Chemical Inventory Item/Stressor	*Initial Impact to Ecosystem*
♦ land fragmentation	♦ habitat alteration
♦ construction	♦ habitat destruction, alteration
♦ heat discharged (energy production output)	♦ heat damage, dispersion of heat, ecotoxicity
♦ change to water quality • TSS	♦ stress on aquatic species
♦ change to water quantity	♦ interrupted drainage (surface, subsurface), change in aquifer level, change in stream base flow
♦ compaction, paving or application of an impervious soil coverage	♦ effects on soil moisture, aquifer recharge, habitat destruction

Table 2-8 Sample chemical stressors (Pollution) and their contribution to potential human health impacts

Chemical Inventory Item/Stressor	*Initial Impact to Human Health*
♦ toxic compounds to air	♦ toxic effects
♦ toxic compounds to groundwater	♦ toxic effects
♦ toxic compounds to soil	♦ toxic effects

Table 2-9 Sample resource depletions and their contribution to potential natural resource impacts

Flow and Stock Resource Inventory Item/Stressor	*Initial Impact to Natural Resources*
♦ fossil fuel use/energy consumption	♦ primary energy source depletion (stock resource depletion)
♦ solid waste	♦ land or space consumption (stock resource depletion)
♦ land stagnation	♦ land or space consumption (stock resource depletion)
♦ water use	♦ water use (flow resource use)
♦ mineral use	♦ mineral consumption (stock resource depletion)

For this study, resources include any components of the natural environment (air, land, water and biota) and exclude processed natural materials. There are two categories of natural resources specified: flow resources (i.e., renewable) and stock resources (i.e., non-renewable). It may be important to distinguish between scarce renewable resources (e.g., hardwood) versus "more abundant" renewable resources (e.g., softwood). "Land stagnation" is a stressor developed to reflect contaminated sites that remain contaminated and consequently cannot be used for other purposes.

2.5.2 Characterization

Characterization involves translating stressors into impacts by means of models, such as equivalency factors. The objective of characterization is to convert and aggregate inventory data into common units that have environmental significance [SETAC 1997]. Few models exist to translate inventory data into impacts. SETAC [1997] lists and discusses models available for LCIA. Due to the importance of toxicity concerns, which underlie the motivation for site remediation, we focus on appropriate assessment models and discuss the need for impact models that treat the site-specific impact of land use. As mentioned earlier, we distinguish between process and site-related impacts in order to address effects arising from site remediation both systematically and comprehensively

PROCESS-RELATED TOXICITY ASSESSMENT

Ecological and human toxicity are important metrics for both process- and site-related impacts. For process-related chemical emissions (in contrast to soil and groundwater contaminants), we suggest following approaches detailed by Guinée and Heijungs [1993] and Jia et al. [1996]. This approach uses a multi-media Mackay model (e.g., Level III fugacity model of Mackay et al. [1992]) coupled with toxicity data that are commonly used in risk assessment (e.g., TDI or tolerable daily intake). The analysis is suitable for assessing chronic or long term toxicity effects for persistent chemicals. Fugacity is preferred for chemicals that partition among media (e.g., chemicals that have a measurable vapour pressure). For chemicals lacking a measurable vapour pressure such as metals, an alternative equilibrium criterion, aquivalence, must be used [Mackay and Diamond 1989]. The multi-species formulation should be used for chemicals that exist as multiple, interconverting species such as mercury [Diamond et al. 1993]. Using a multi-media model coupled with toxicological benchmarks accounts for differences in chemical mobility, tendency to bioaccumulate, toxicity and, within a limited range, persistence. For human health assessment, databases are available with toxicological benchmarks relevant for exposure via air or ingestion. Guinée and Heijungs [1993] suggest methods for assessing ecosystem health, while acknowledging that they are far less well developed than for human health.

The analysis yields media- and chemical-specific ratios of estimated-to-allowable exposure, analogous to the Hazard Quotient used in risk assessment. The allowable exposure is a "no-effect" level for threshold or non-carcinogenic chemicals, or for carcinogens, a dose that results in a specific risk of, for example, 10^{-6}. Using the method detailed by Jia et al. [1996] allows for consideration of multi-media transfer from the compartment receiving the emission to that where exposure is calculated. The approach is not suitable for highly reactive, toxic chemicals that can exert acute effects close to the point of emission, or spill conditions. For these chemicals a dispersion or "point-of-impingement" model may be necessary, again coupled with a toxicological benchmark.

SITE-RELATED TOXICITY ASSESSMENT

Concerning site-related impacts, the multi-media approach suggested above is not well suited to characterizing the effects of contaminants remaining in soil and groundwater following remediation since groundwater is not presently included in the model and multi-media fate is not necessarily of primary importance. To address site effects, we suggest using a model that specifically treats the persistence and mobility of soil and groundwater contaminants. Estimated contaminant concentrations should then be linked to toxicity effects for human and non-human receptors using a method analogous to that suggested by Guinée and Heijungs [1993]. Thus, this

Table 2-9 Sample resource depletions and their contribution to potential natural resource impacts

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♦ solid waste	♦ land or space consumption (stock resource depletion)
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♦ water use	♦ water use (flow resource use)
♦ mineral use	♦ mineral consumption (stock resource depletion)

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OTHER INDICATORS

As previously mentioned for LCM, metrics expressing on-site "quality" are necessary because soil and groundwater are included within the system boundary, and are used to assess the effectiveness of the remediation. We propose to describe overall site "quality" using a suite of site quality metrics such as soil moisture, organic content, porosity and drainage.

In addition to assessing the potential effects of contaminants left on-site and characterizing soil quality, a metric is necessary for expressing land use, or conversely land rendered unusable or hazardous due to contamination. By "land use" we refer to the potential use of the land for habitat and to support biodiversity, or for agriculture, residential, or industrial purposes, any of which relate back to the ultimate goal of the remediation. Land use affects the site itself, as well as sites used for soil disposal and to obtain clean fill. "Solid Waste Burden" (SWB) is a volumetric indicator used to reflect the space occupied by waste and reflects landfill burdens, thereby circumventing spatial (e.g., area) issues. Alternately, a simple metric reflecting "useable land area" (e.g., spatial dimension of land) may be employed however, the "use" of the land must be specified since not all uses are equally productive or desirable (e.g., use for habitat versus industrial development). Obviously, difficulties arise when attempting to use one metric to reflect all facets of land use. We therefore propose using, at the least, the SWB metric coupled with the "useable land area" to reflect land issues.

2.6 CONCLUSIONS

We have described a life-cycle based approach to examine potential environmental and health impacts associated with contaminated site remediation options. To consider the challenges arising from remedial activities, a Life-Cycle Framework was developed consisting of modified LCM and LCA methods. As with any LCA, the final results are sensitive to methodological assumptions and procedures.

The LCM approach helps to identify and clarify aspects of site remediation that contribute most to the environmental burden of remediation, and involves four major steps: *Identify*; *Inform*; *Assess*; and *Implement*. The LCM approach offers insight at a basic level, whereas the modified LCA may be used for a more thorough examination. We have modified the LCA approach as follows: setting the temporal boundary at 25 years to capture and average impacts occurring over the long and short term; including soil within the process boundary; defining mass or volume of treated soil as the functional unit; redefining the life-cycle stages; and establishing two suites of impact assessment metrics (those related to site quality and another to process-related activities). The LCF may be used for design of site remediation approaches or to analyze remediation case studies.

3. LCF SURVEY OF SITE REMEDIATION OPTIONS

3.1 INTRODUCTION

The purpose of this Chapter is to illustrate and assess the LCM component through application to six commonly used site remediation options. The analysis is general, rather than site-specific, with the aim of identifying the main environmental and health concerns associated with each method. The remediation options are methodically explored and presented according to the components of the LCM approach: *Identify*; *Inform*; and *Assess*. The options chosen include in-situ and ex-situ methods, and encompass physical, biological and management remediation methods. Physical methods include in-situ vapour extraction, excavation and off-site disposal, and ex-situ soil washing. In-situ bioremediation is the biological method and encapsulation is the management method investigated. The no-action, or status quo option, is also included since it is often considered as a point of comparison (e.g., control scenario) or as a reasonable option despite not reducing the toxicity, mobility, or the volume of the contaminant in the soil. For each remediation option, a description of remediation activities, generic process flow charts, lists of typical inputs and outputs, and potential impacts are presented. The options are compared qualitatively based on potential impacts and we conclude with a discussion of the application of the LCF to remediation options. Process descriptions are derived from City of Toronto [1991] and additional references as noted.

3.2 LCM FOR SIX REMEDIATION OPTIONS

Below, we discuss the six remedial options according to the components of LCM. The qualitative analysis is presented according to the LCM stages: *Identify*; *Inform*; and *Assess*. The options considered include: no-action, encapsulation, excavation and disposal, vapour extraction, in-situ bioremediation, and soil washing. No-action has been included because maintaining the status quo is always an option for a contaminated site, despite a fundamental lack of management or treatment technology. The results of the analysis are predominantly illustrative.

3.3 *IDENTIFY*

The first step of *Identify* is to clarify the study's purpose, which helps to maintain a focused study and suggests the extent of information or assessment required. Clarification entails specifying the study's application, assessment goals, end users and boundaries. For this study, the purpose is to improve our understanding of the potential environmental burdens of six generic remediation options, consequently a qualitative study is appropriate. The end users of the research include those interested in the environmental implications of remediation activities such as policy makers, large land holders and consultants. The temporal boundary is long term and the geographic boundary includes all sites affected (e.g., hazardous and non-hazardous waste disposal facilities, and borrow pits for clean fill). Here, the process boundaries encompass all major processes or activities; we neglect secondary processes for the sake of simplification.

The remedial options are described by outlining all major activities over the entire life cycle according to "life-cycle stages" for remediation options: raw materials and energy acquisition; site-processing; and post site-processing. Life-cycle sub-stages that may be associated with any life-cycle stage(s) include transportation and distribution, waste management, and monitoring. Dissection into particular categories is not important, but only that all activities are included and reported. For this study, the major activities and flow charts of each remediation option are described below, with numbering corresponding to descriptions in Table 3-1.

3.3.1 No-Action (1)

No-action involves leaving contaminants on-site without intervention (Figure 3-1). The contaminants will distribute into air, water, soil and sediment on- and off-site according to their physical-chemical properties and environmental characteristics, and may degrade or be transformed [Paustenbach 1989, Asante-Duah 1996]. Whereas human activities do not occur, there are several consequences that result from this remedial approach: land use impairment due to the presence of contaminants (1a); potential toxicological effects arising from contaminants remaining on-site (1a); air emissions (1b); and water emissions (1b).

Figure 3-1 Flow chart for no-action (1)

3.3.2 Encapsulation (2)

Encapsulation isolates the contaminated soil and groundwater by means of walls or panels and surface caps. Typically, encapsulation (Figure 3-2) involves: excavating a trench around the contaminated area until an impermeable sub-surface layer is reached (2a); transporting materials and equipment for walls and cap (2e), and equipment for excavation (2b); producing impermeable walls/panels (2d); and filling the trench with these impermeable walls/panels (e.g., clay, clay slurry, concrete, sheet piles) (2c) [Russel 1992, Caldwell and Reith 1993]. If an impermeable subsurface layer is not found at a reasonable depth, an impermeable base is constructed (2c). Material(s) for surface caps are produced (2g) and then applied (e.g., impermeable soils, soil admixtures, synthetics, clay (2f)) [Russel 1992]. Finally, caps and walls are subject to long term monitoring (2h) and maintenance (2i).

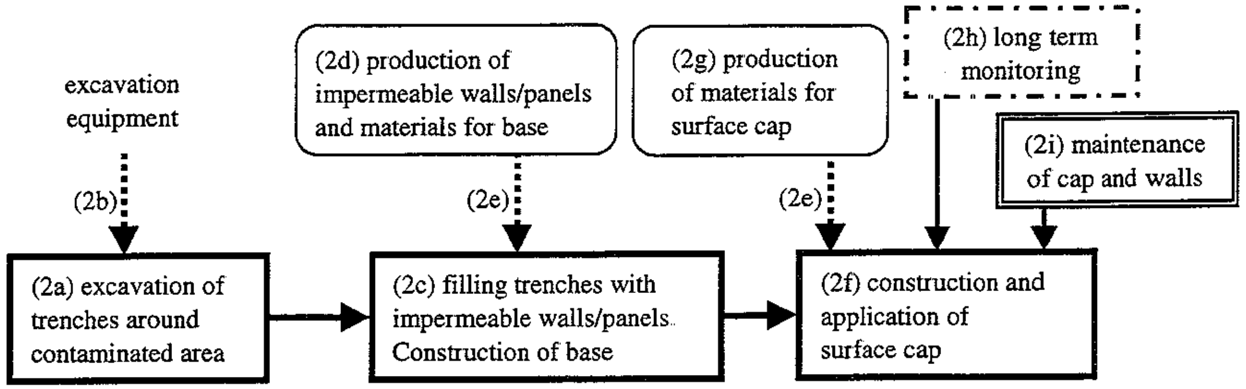


Figure 3-2 Flow chart for encapsulation (2)

3.3.3 Excavation and Disposal (3)

Excavation and off-site disposal of contaminated soil removes contaminants from the site for deposition in either hazardous or non-hazardous landfill sites, depending on the level of contamination. The main activities (Figure 3-3) include: excavation of contaminated soil (3a); dust mitigation procedures (3b); pumping and treating groundwater and process water (3c) [Cole 1994]; transporting soil and water treatment sludge off-site (3d) [Bellandi 1998]; disposal of soil and sludge in a hazardous and/or non-hazardous landfill site (3e); and discharge of treated water to sewers (3f). Clean soil for backfill is excavated (3g), transported to the site, and placed in the excavation pit (3h). The landfills are monitored (3i) and maintained over the long term (3j) [Laidlaw 1994].

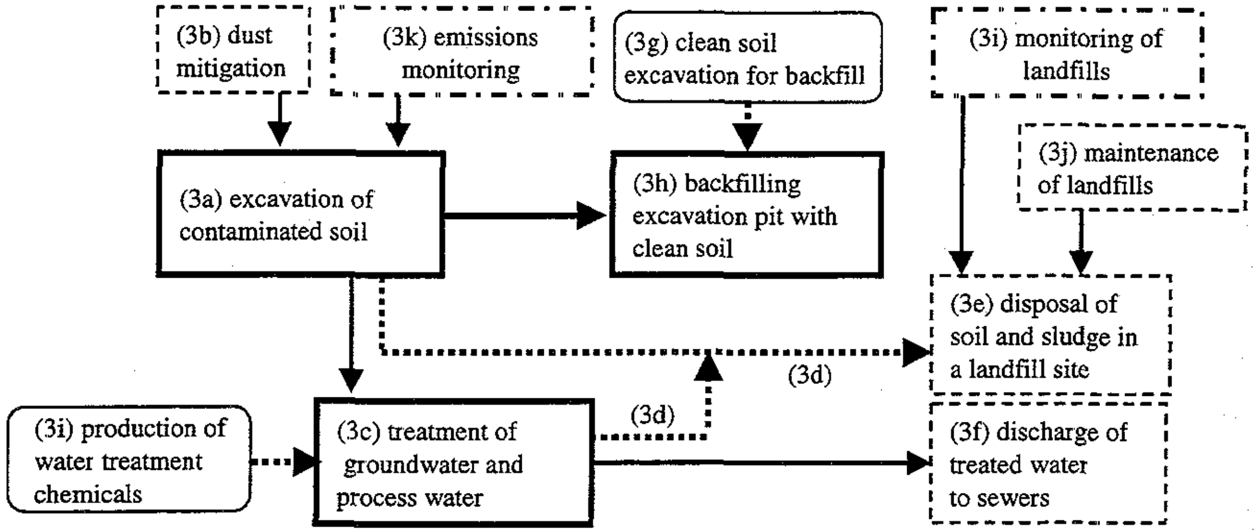


Figure 3-3 Flow chart for excavation and disposal (3)

3.3.4 In-Situ Bioremediation (4)

In-situ engineered bioremediation involves microbial degradation of contaminants that may be augmented by adding, for example, oxygen (e.g., air, oxygen, hydrogen peroxide), nutrients (e.g., phosphorus, nitrogen), acids or bases to control pH, surfactants to mobilize trapped contaminants, and organic co-substrates [Truex et al. 1994, Norris and Matthews 1994]. The main activities (Figure 3-4) include: drilling a network of injection and extraction wells for hydraulic control of contaminated groundwater (4a); recovering free product present as a distinct non-aqueous phase (4b); treating and returning groundwater (hydraulic control) (4e); capturing volatile organic compounds (VOCs) from wells (4d); and pumping groundwater to increase the flow and movement of nutrients and oxygen (4f). Compounds used to augment degradation are produced (4c) and injected along with water and oxygen. Indigenous organisms may be removed from the site for selection, enrichment and reintroduction, or they can be augmented with genetically engineered organisms (4g) [McEldowney et al. 1993]. Clean-up progress is assessed through monitoring (4h).

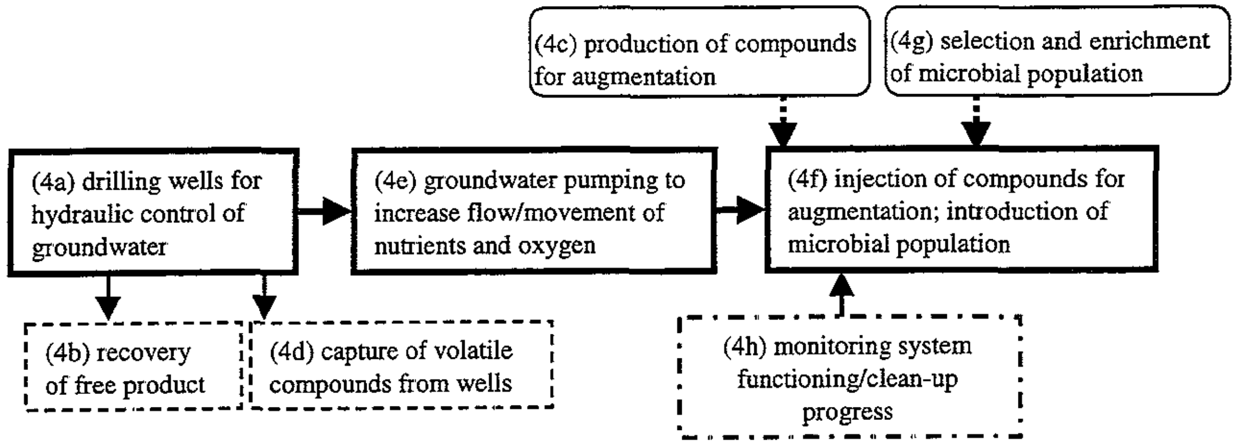


Figure 3-4 Flow chart for bioremediation (4)

3.3.5 Soil Washing (5)

Soil washing is an ex-situ soil treatment process capable of separating a wide variety of contaminants into a concentrate of soil fines, leaving a "clean" coarse fraction [Anderson 1993, NGSRP 1991]. The major activities (Figure 3-5) include: soil excavation (5a); transportation of excavated soil to pretreatment and soil washing facilities (5b,k); soil preparation (5c) (e.g., breaking, crushing, blending or rejecting oversized material); soil washing (5f) (soil is mixed, washed, and rinsed with water and/or solvents or reagents); and soil recovery in two fractions (a clean coarse fraction and the contaminated silt and clay fraction). The extracting agents and treatment chemicals are produced (5d) and transported to the soil washing facility (5e). The contaminated process liquid is treated (5g), resulting in liquid treatment residuals (sludge) and contaminated fines that are managed through disposal as landfill (5h), and process water that is discharged to surface waters (5m). The washed coarse fraction may be returned to the site as clean backfill, but requires soil amendments to improve soil quality. On-site monitoring occurs for fugitive dust and volatile emissions (5l), and long-term maintenance and monitoring of landfills is necessary (5i,n).

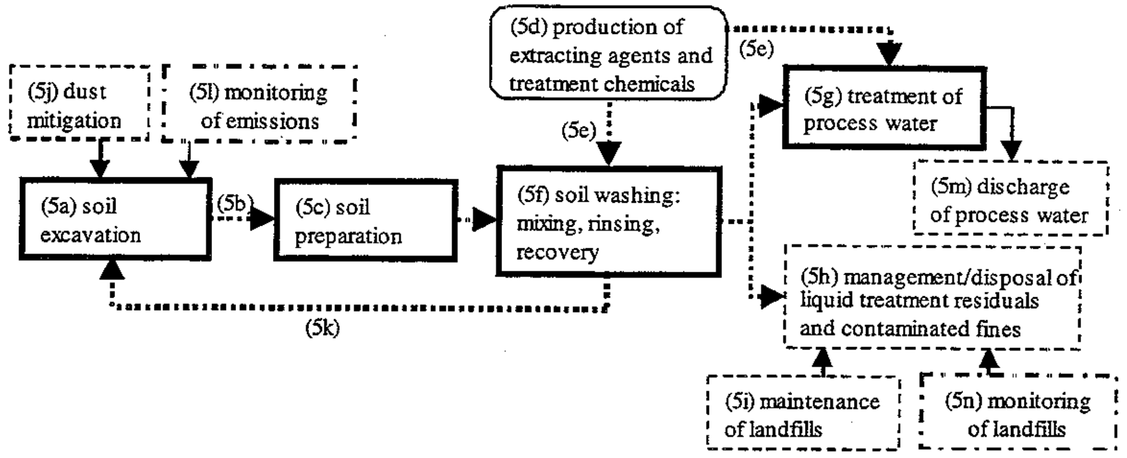


Figure 3-5 Flow chart for soil washing (5)

3.3.6 Vapour Extraction (6)

Vapour extraction involves applying a negative pressure to the soil via aboveground vacuum pumps connected by airtight piping to extraction wells [Fam 1996]. The negative pressure removes air, moisture and the vapour phase of VOCs and semi-volatile chemicals from the soil surrounding the extraction wells. In some cases, clean heated air may be pumped into the soil through injection wells [Cole 1994], or allowed to flow through inlet wells [Chambers 1991]. The air and water are separated, and the contaminated air is treated using, for example, activated carbon adsorption, or a variety of options that may include thermal destruction, catalytic oxidation, condensation, biological degradation, or ultraviolet oxidation. Carbon adsorption is the treatment considered in this study. The clean air is finally vented. As shown in Figure 3-6, typical activities can be summarized as: drilling of injection, extraction and monitoring wells (6a); applying negative pressure and pumping heated air to soil (6b); pumping air, water and chemicals to an air-water separator (6c); separating air and water (6d); production of treatment compounds (6e) (e.g., activated carbon); treating contaminated air and water (6f,g); discharging treated water and air (6h,i); transportation to, and disposal of, residuals in a hazardous landfill site (6j); and regeneration of activated carbon. Receiving landfills require long term monitoring and maintenance (6k,l).

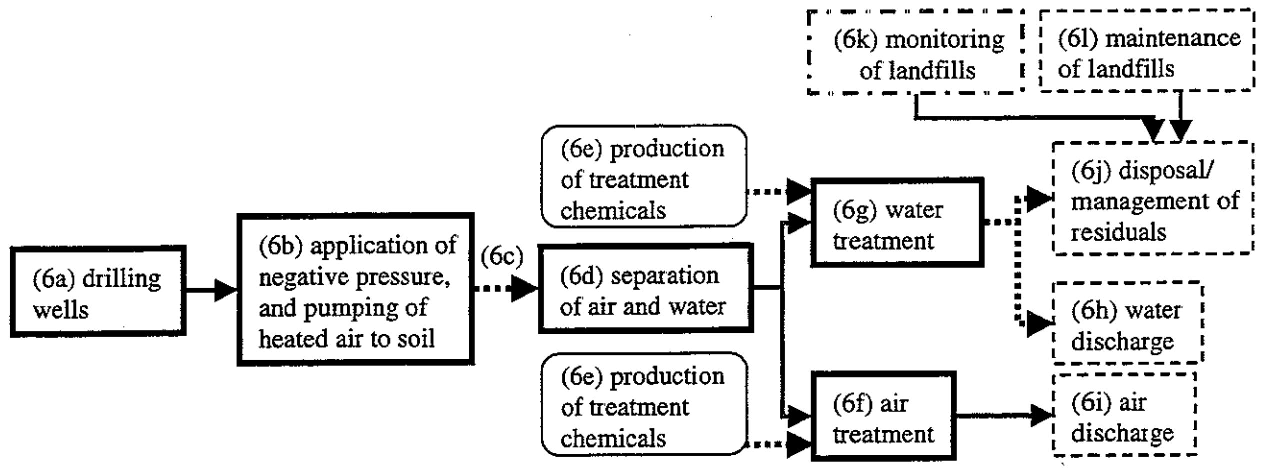


Figure 3-6 Flow chart for vapour extraction (6)

3.4 *INFORM*

The second component of LCM, *Inform*, involves compiling information on the inputs and outputs of each remediation option, based on the processes and activities described. Because of the study's purpose, information in the inventory is qualitative. The inventory involves recording items such as material and energy resources, air and water emissions, and soil wastes. Non-traditional items must also be noted, such as information on land use (e.g., consumption of space), or land associated with possible ecosystem and landscape degradation (e.g., location of valuable habitat, impervious surfaces, land fragmentation, land stagnation). Equipment or infrastructure used during the remediation (e.g., pumps, excavation equipment, separators, transportation vehicles) are not usually included in LCA or LCM analysis [CSA 1994]. Table 3-1 lists typical inventory items for each remediation option with numerical reference to the activities described in the section above.

Table 3-1 Typical inputs, outputs and other information for remediation options

[Numbering following the inputs, outputs, and other information refers to those in Figure 3-1 to 3-6]

Inputs	*Outputs*	*Other Information*
No-Action none	*Air Emissions* • volatile contaminant emissions (1b) *Water Emissions* • migration of contaminants in groundwater (1b)	• non-remediation of land (1a) • contaminants remain in place (1a) • negative social perception of site (1a)
Encapsulation *Material Resources* • jetting fluids (2a) • grouting (2c) • panels: steel panels (2c,d) • membrane walls (2c,d) • surface cap layers (2f) *Energy Resources* • diesel (2a, b,c,d, e,f,g)	*Air Emissions* • dust (2a) • volatile contaminant emissions (2a) • transportation-related emissions (2b) *Water Emissions* • contaminated cutting fluid (2a)	• diversion of groundwater (2a,c) • alteration of groundwater recharge (2f) • noise, vibration (2a) • space needed for construction of some walls (2c) • possible contaminant leakage, or breaches in wall integrity (2h,i) • site use limited to surface (2f) • contaminants remain in place (2c,f)
Excavation and Disposal *Material Resources* • wastewater treatment chemicals (3l) • clean backfill (3g) *Energy Resources* • diesel (3a,c,d,g,h,l)	*Air Emissions* • dust (3a.e.g) • volatile contaminant emissions (3a,e) • transportation-related emissions (3a,d,g,h) *Solid Wastes* • hazardous/non-hazardous soil and sludge (3e) *Water Emissions* • treated process ground water (3f)	• noise (3a,d,h) • space consumption at landfill (3e,j) • off-site excavation (3g)
Bioremediation *Material Resources* • compounds for augmentation (4c) • non-contaminated water (4f) • nutrients (4f) • electron acceptors (4f) • acid/base for pH control (4f) • microbial population (4g,h) *Energy Resources* • diesel, other (4a,e,f)	*Air Emissions* • dust (4a) • volatile contaminant emissions (4a,b,d)	• noise (4a) • alteration of indigenous microbial population (4f,g) • alteration of natural groundwater flow (4a,e)
Soil Washing *Material Resources* • surfactants and chelating agents, other treatment chemicals (5d) • clean soil (if necessary) (5i) *Energy Resources* • diesel, other (5a,b,c,e,f,g,h.k)	*Air Emissions* • dust (5a,c) • volatile contaminant emissions (5a,c) • transportation-related emissions (5b,e.k) *Solid Wastes* • disposal of fines and water treatment residues (filter cake) (5h) *Water Emissions* • *process water (with some treatment* chemicals) (5m)	• noise (5a b c,f,j) • alteration of groundwater flow (5a) • space consumption at landfill (5h i)
Vapour Extraction *Material Resources* • treatment chemicals for air (e.g. activated carbon) (6e) • treatment chemicals for water (6e) *Energy Resources* • diesel, other (6a,b,c,e,f,g)	*Air Emissions* • treated air (6i) *Solid Wastes* • residuals (6f.g,j) *Water Emissions* • treated water (6h)	• noise (6a.c) • space consumption at landfill (residuals) (6j) • heating effects on soil (6b)

The next step of *Inform* involves linking inventory items, or groups of items (Table 3-1), with potential environmental and human health impacts. At the simplest level of LCM, this involves identifying stressors associated with all stages of the remedial option under consideration, using a "Potential Impacts Checklist". This checklist is a LCM tool that was developed specifically for remediation activities, and itemizes stressor-potential impact links. The purpose of using this checklist is to highlight potential concerns and ensure that potential impacts associated with any remediation activities are neither overlooked nor ruled out.

Three levels of concern reflect the severity of potential impacts: (i) no or low concern; (ii) moderate concern; and (iii) high concern [Campbell et al. 1995]. We have developed qualitative criteria to guide the ranking process. For all stressors, "no or low concern" refers to a lack of, or negligible presence or concern regarding the stressor in question. Ranks of "moderate" or "high concern" are assigned based on the following criteria: (a) discharge amount or emission rate; (b) timeframe of disturbance; (c) reversibility of disturbance; (d) ability to control or contain process or emission; and (e) ability to monitor or verify process or emission (i.e., uncertainty). Further guidance for ranking is given below, according to the main stressor categories of *Pollution*, *Disturbance*, and *Depletion*. The ranking of stressors presented in Table 3-2 reflects our current interpretation of the inventory information (Table 3-1) and the judgement of a multidisciplinary team.

Pollution stressors can be ranked according to amounts emitted, with attention given to potency. For process-related impacts, regional concerns can be considered when ranking acid emissions, air pollutants and photochemical smog, nutrients, process water quality and toxic air contaminants, based on knowledge of the receiving environment, e.g., low alkalinity or oligotrophic receiving waters, emissions of smog precursors to areas exceeding air quality guidelines. In contrast, site-specific stressors relate to effects of chemicals remaining on-site, with attendant eco- and human toxicological implications, and the ability for ecosystem regeneration. Thus, options with low removal efficiencies will receive "high concern" rankings for these stressors. Chemical soil quality stressors (e.g., nutrient levels, organic carbon content, microbial population, pH) refer to soil changes relative to pre-remediation conditions.

Disturbance stressors contribute to non-chemical consequences of remediation and related activities. Off-site construction, excavation, and land fragmentation are a high concern if they are unavoidable and affect off-site land use over the long term. No-action and encapuslation are designated a high or moderate concern if the remediation options render most or part of the site, respectively, unavailable for new potential uses. Stressors indicating site-specific aquifer quality refer to changes in groundwater quantity that could result from capping, adding barrier walls, or changing aquifer characteristics by replacing native soils with, for example, coarse fill. Non-chemical soil quality stressors (e.g., porosity, soil particle size) are a high concern if the soil composition is changed. Human soil stressors include noise, dust, odour, vibration, changes to aesthetic value, and psychosocial effects. Due to the variety of effects, designating a particular level of concern may be difficult.

Depletion stressors refer to the use of resources relative to their stock or flow. Regional specificity may be incorporated in the ranking, such as water use relative to its abundance, or contaminated soil excavate relative to land available for disposal.

Assigning levels of concern can be challenging because of the varied nature of information available for each technology, as noted by Campbell et al. [1995]. However, unlike their study, assigning ranks is guided by the inventory data that are related to the stressor-potential impact links established as part of LCM (i.e., Potential Impacts Checklist).

In this study, members of the investigation team independently ranked the concern levels for each item of the six technology types. Group discussion led to refining the final ranking for each item, thereby minimizing inter-rater discrepancies. Although the rating process is subjective, bias is minimized by the multiple appraisers working from Inventory data towards consensus. This approach is derived from methods on conducting Systematic Reviews [North York Public Health Department 1997] that require two or more appraisers to independently apply a "Quality Assessment Tool" to determine the quality of a specific scientific study. The level of inter-rater agreement is noted, and consensus is reached on the final subjective rating

Table 3-2 Potential Impacts Checklist for remediation options

[Note: • and ◊ denote process- and site-related stressors, respectively. Levels of concern are: "no or low" (☐), "moderate" (☒), and "high" (■).]

Stressor Categories	*Potential Impact Categories*	*Levels of Concern for Remediation Options*					
		No-Action	**Encapsulation**	**Dig & Haul**	**In-Situ Bio-remediation**	**Soil Washing**	**Vapour Extraction**
Pollution							
•acid emissions(a)	→acid rain	☐	☐	■	☐	☒	☐
•greenhouse gases(b)	→global warming	☐	☒	■	☒	☒	☐
•ozone depleting substances(c)	→ozone depletion	☐	☐	☐	☐	☒	☐
•air pollutants and photochemical smog(d)	→air pollution	☐	☐	■	☐	☒	☐
•nutrients discharged	→eutrophication	☐	☐	☐	☒	☐	☐
•process water quality stressors	→stress on aquatic species	☐	☒	☒	☐	☒	☒
•toxic contaminants and particulates to air	→airborne transport to other media(e)	■	☐	■	☒	■	☒
	→human health impairment(f)	■	☐	☒	☐	☒	☒
◊toxic contaminants in surface and ground water(g)	→ecotoxicity impacts	■	■	☐	☒	☐	☒
	→human health impairment(f)	■	☒	☐	☒	☐	☒
◊toxic contaminants in soil(g)	→ecotoxicity impacts	■	■	☐	☒	☐	☒
	→*human health* impairment(f)	■	☒	☐	☒	☐	☒
◊chemical soil quality stressors(h i)	→soil quality disturbances	☐	☐	☒	■	■	☐
Disturbance							
•heat discharge	→heat damage/dispersion of heat	☐	☐	☐	☒	☐	☒
•off-site construction, excavation, or land fragmentation	→habitat alteration or destruction	☐	☐	■	☐	☒	☐
◊non-remediation of land	→land stagnation	■	■	☐	☐	☐	☐
◊compaction, paving, or application of an impervious soil coverage	→effects on soil moisture, aquifer recharge, ecosystem regeneration	☐	■	☐	☐	☐	☐
◊aquifer quality stressors	→interrupted drainage, changes in aquifer level, changes in stream base flow	☐	■	☒	☒	☒	☐
◊non-chemical soil quality stressors(h,j)	→soil quality disturbances	☐	☐	☒	☐	■	☐
•human social stressors(k)	→human social disturbances	☒	☐	☒	☐	☒	☐
Depletion							
•fossil fuel use/ energy consumption	→primary energy source depletion	☐	☒	■	☐	☒	☒
•solid waste	→land or space consumption	☐	☐	■	☐	☒	☐
•water use	→water consumption	☐	☐	☒	☐	☒	☐
•mineral use	→mineral consumption	☐	☐	☐	☐	☐	☐

(a) e.g., SO_x HCl, NO_x particulates; (b) e.g., CO_2, CFCs, methane, methyl chloride; (c) e.g., CFCs, CO, methyl furan, methyl chloride; (d) e.g., VOCs, semi-volatile compounds, PAHs, NO_x, SO_x, particulates; (e) ecotoxicity; (f) human toxicity; (g) migrating or remaining in surface water, groundwater, or soil; (h) affecting or changing the original (i.e., pre-remediation) soil quality; (i) e.g., nutrient levels, organic content microbial population, pH; (j) e.g., porosity, soil particle size; (k) e.g. noise, dust, odour, vibration, aesthetic value. psychosocial effects.

3.5 ASSESS

The extent of analysis at this stage depends on the study's goal which, for this study, is to investigate generic remediation options to better understand their potential environmental and human health impacts. To address this objective, we highlight significant stressors and their related potential impacts from the Potential Impacts Checklist (Table 3-2).

For the *no-action* scenario, the stressor categories of concern are site-related. The contaminants on-site remain untreated, therefore the land remains stagnant and unavailable for other uses. As well, the contaminants pose a potential risk to ecological and human health on- and off-site. Contaminants may move off-site by migration via groundwater, and soil erosion and volatilization can result in airborne chemical transport and/or movement to surface waters. Important stressors include contaminants in surface water, groundwater and soil, which may remain on-site or migrate off-site.

Encapsulation minimizes contaminant migration and therefore off-site exposure to biota and humans, however, contaminant concentrations on-site are not intentionally reduced. Consequently, the land is partially restricted for other uses (i.e., limited to surface use only). The addition of an impervious surface (e.g. cap) and barriers represents a major disturbance to the site and environs (e.g., soil moisture, aquifer level, stream base flow, potential ecosystem regeneration). Since on-site contaminant concentrations are not altered, encapsulation may be associated with on-site toxicity impacts through groundwater and soil, impacts to the surrounding aquifer (e.g., groundwater flow), ecosystem regeneration, and land stagnation.

For *excavation and off-site disposal*, the major stressors and potential impacts are process-related. Contaminants, particularly VOCs, are released to air during excavation. Chemical emissions to air also come from activities such as on- and off-site transportation, with transportation-related impacts occurring as a function of distance traveled (e.g., to waste disposal site, from backfill source). These emissions result in potential effects on air quality and global warming. Energy source depletion (e.g., transportation fuel) is also a concern arising from transportation activities. Excavation of backfill (i.e., for cleanfill) affects land use at the borrow pit. Finally, disposal of the solid waste produced, which may be hazardous and/or non-hazardous soil, leads to land consumption, and energy and resource use that accompanies long term maintenance and monitoring at the receiving site(s).

Reducing contaminant concentrations by *in-situ bioremediation* can be a long term enterprise. Thus, significant stressors relate to contaminants remaining on-site or migrating off-site, which could contribute to ecosystem and human health impacts. Nutrients injected into the soil to promote contaminant biodegradation may be discharged or leach into surrounding surface waters or groundwater, thereby contributing to eutrophication. Groundwater pumping to remove contaminants and promote oxygen and nutrient exposure may affect aquifer quality. All activities may alter the site's indigenous microbial population (e.g., introduction of genetically engineered microbial population) and soil quality. In some cases this alteration may be positive, such as nutrient addition and soil aeration.

Soil washing treats excavated soil relatively rapidly but with attendant emissions resulting in on- and off-site impacts. Excavation prior to treatment and soil preparation may result in emissions of VOCs and contaminant-sorbed dust, similarly to that for excavation and disposal. On-site, the process alters soil quality (e.g., nutrient levels, organic content, particle size distribution) which has a secondary effect on land use or requirements for ecosystem regeneration. Fossil fuel combustion for transportation and process energy results in off-site chemical emissions to air with attendant impacts of air pollution, acid rain and global warming, as well as resource consumption. Since soil washing essentially separates a coarse, clean fraction from the contaminant-sorbed fines, the latter requires disposal (e.g., residuals and contaminated fines) that leads to land or space consumption and long term monitoring and/or maintenance at the recipient site. Clean backfill may be required to rehabilitate the site, causing disturbance at the borrow pit. Water may be consumed, although process water is often recycled.

As for in-situ bioremediation, significant stressors for *vapour extraction* are site-related, involving potential ecosystem and human health impairment associated with contaminants remaining on-site in soil and groundwater during the often lengthy remediation process. Solid waste associated with water and air treatment requires disposal, which may contribute to land or space consumption.

3.6 DISCUSSION OF LCM ANALYSIS

The LCM approach illustrated here can be used to broadly and systematically consider potential impacts associated with site remediation options. The intent of LCM is to be inclusive by spanning the "life cycle" of a remediation option and expanding the analysis beyond the contaminated site itself. Considering a long time frame equalizes or amortizes burdens that may be considerable but occur over a short time period (e.g., soil washing) compared with lower impacts occurring for a prolonged time (e.g., no-action, the disposal side of excavation and disposal). By broadening the analysis in these ways, "hidden" or externalized impacts are identified, which could change the desirability of options.

The investigation of six remediation options by means of LCM, has highlighted major differences in their concerns beyond those deduced from other commonly used assessment methods. "Non-treatment" options address contaminated sites through either decisions (i.e., no-action), management (i.e., encapsulation), or removal of both the soil and contaminants from the site (i.e., excavation and disposal). The impacts related to taking no remediation action are potential ecosystem and human health burdens due to contaminants remaining on-site and restrictions on land use. No-action and encapsulation limit land use possibilities at the site, whereas excavation and disposal leads to land consumption elsewhere (e.g., hazardous landfill facility, backfill source). Encapsulation does not mitigate on-site ecosystem impacts, however it addresses the potential human health burdens by isolating the contaminants. Excavation and disposal reduces site-related impacts by transporting the contaminants from the contaminated site to a receiving site where contaminant migration and exposure are controlled. The transportation necessary with the excavation and disposal option contributes to transportation-related impacts of air quality impairment and resource consumption.

The "treatment" options considered here reduce contaminant levels through technology. The potential impacts from vapour extraction and in-situ bioremediation relate largely to contaminant removal efficiency, where the contaminants remaining on-site during and after the often lengthy clean-up contribute to ecosystem and human health impairment. For in-situ bioremediation and soil washing, on-site aquifer quality may be affected and off-site water quality can be impaired by the discharge of compounds used in the treatment processes. Soil washing contributes to off-site land consumption since contaminants must be discarded at a receiving site, although the volume discarded is much less than the original volume of contaminated soil. As well, resources are required to maintain the disposal site(s) over the long term.

The LCM approach used to clarify potential impacts is conceptually simple, requires qualitative data, and can be used with relative ease when assessing numerous options. Thus, it is flexible and broadly applicable. Perhaps the most effective use of the approach is to promote "life-cycle thinking", and to methodically investigate and highlight potential, often ignored, or discounted impacts associated with a remediation approach. A concern arising when using a simplified approach versus the more rigorous LCA, relates to "streamlining" issues in which unforeseen subtleties may be overlooked or neglected leading to distortions [Todd 1996]. These concerns, which can also pose challenges in a quantitative analysis, can be mitigated by using a consultative process and peer review, as has been done here.

The ability to conduct a LCM and more in-depth studies lies in the intensive research and survey of literature required. Detailed information is essential for the *Inform* and *Identify* components of LCM, and the quality of the information affects the overall quality of assessment.

Another important concern regarding the LCM approach relates to the use of expert judgment when assigning the various levels of concern in the Potential Impacts Checklist. The assignment relies on the practitioner's expertise to approximate the relative importance of the various stressors for the remediation option(s) based on a qualitative inventory. Bias in the rating process can be minimized by an initial, independent assessment by multiple appraisers and then reaching consensus through discussion. The intent of the Checklist is to emphasize a broad range of potential impacts rather than relying on a few criteria.

In addition to environmental and human health impacts, the inclusion of other major considerations such as cost, appropriateness of treatment, community disturbance, or completion time, will ultimately form the ideal framework. As with many evaluation methods, the final outcome depends on those conducting the evaluation, which argues for multi-stakeholder involvement and peer review. Finally, the LCF approach is not intended to be used in place of risk assessment, which focuses exclusively on toxicity, or other site-specific assessment tools. Rather, LCF provides insight into a wide range of potential impacts, including those that could occur on a site-specific basis (e.g., aquifer quality), and at regional and global scales (e.g., acid rain and global warming, respectively).

3.7 CONCLUSIONS

We have presented a Life-Cycle Framework and illustrated the application of one of its two components, a Life-Cycle Management approach for highlighting the environmental and human health impacts associated with contaminated site remediation options. The Life-Cycle Framework provides a systematic investigation of activities associated with site remediation, and facilitates the analysis of a variety of potential environmental, human health, and resource impacts. The LC Framework promotes the consideration of a wide range of potential impacts, expanding consideration beyond contaminated sites themselves. Possible uses of the Life-Cycle Framework, therefore, lie in providing an environmental and human health perspective for decision-making, such as choosing an option or identifying stages within an option that contribute significantly to the overall burden.

Applying the LCM approach to six generic options illustrates that no-action and encapsulation options have similar potential impacts related to toxicity, land use and consumption, and ecosystem and human health, since contaminants remain on-site. Excavation and disposal relocates contaminants and, in doing so, results in off-site impacts such as land consumption, and those related to emissions and resource use due to transportation. Potential impacts associated with in-situ bioremediation and vapour extraction relate to contaminant removal efficiency and, for the former, changes to aquifer and soil quality. In-situ bioremediation and soil washing could cause adverse effects through the discharge of process chemicals. For soil washing, along with excavation and disposal, concern exists for potential air quality impairment due to excavation and transportation, and land productivity related to disposing contaminants off-site and obtaining clean backfill.

4. CASE STUDY

4.1 INTRODUCTION

In this chapter we analyze the case study of a contaminated site remediation using LCM and LCA approaches. Whereas the LCM allows for a relatively quick analysis on a qualitative basis, the LCA is quantitative. Quantification enhances the Inventory component and allows more thorough assessment than with the LCM approach. Similarly, the quantitative Impact Assessment clarifies interpretation of the Inventory, albeit for fewer impacts than in the LCM approach. The advantages and disadvantages to both, as applied to a case study, are illustrated in detail below.

4.1.1 Objectives

Our objective is to illustrate and evaluate LCM and LCA for site remediation and secondly, to draw attention to impacts associated with the remediation method examined, that are not usually considered by other assessment methods. The specific research questions addressed include:

1. Can the LCM and LCA approaches be applied to site remediation issues? What new issues arise?
2. What are the environmental and human health impacts associated with the site remediation option?
3. Does the full consideration of issues through LCA change the desirability of the option?
4. Are insights gained through quantification?

4.1.2 Case Study

The case study considered here was a site contaminated predominantly with lead. The remediation activities included soil excavation and deposition in a hazardous waste disposal facility, groundwater and process water treatment, and backfilling the excavation with clean fill from a borrow pit. Thus, the remediation approach examined in this paper is known as a “removal and backfill” or “excavation and disposal”. The case study site was chosen because excavation and disposal is a commonly used method and data of high quality and completeness were available. Excavation and off-site disposal is used frequently because it is considered effective over the long term, reduces mobility of contaminants through landfill containment, and is generally acceptable to the affected community. However, this option does not reduce contaminant toxicity or volume, dust and fugitive air emissions may be generated, and siting new disposal facilities is challenging [U.S. EPA 1989]. Investigating the case study from a life-cycle perspective provides a new perspective on these and other concerns surrounding a widely used remedial approach. The contaminated site and other related sites are located in southern Ontario. For reasons of confidentiality, certain details regarding the site are not presented, however this does not compromise the results presented or conclusions drawn.

4.1.3 Method

The two components of the LCF are used to analyze the case study. The application of LCM is presented in this section according to the four LCM components: *Identify*, *Inform*, *Assess* and *Implement*. This research is qualitative and provides an introduction to, and basis for, the more detailed LCA results that follow. The LCA application involves four components. *Initiation* involves refining the study's goals, bounding the study's scope, describing the remediation activities through process flow diagrams, explaining data issues, and describing assumptions. *Inventory Assessment* focuses on raw materials and energy consumption, airborne and waterborne emissions, and solid waste associated with the remediation and related activities. The *Impact Assessment* was streamlined by using impact indicators for three impact categories: pollution, disturbance and depletion. Finally, *Interpretation* focuses on the remediation activities that contribute most to the selected impact indicators. We conclude with observations on examining the remediation approach from a life-cycle perspective, and a discussion of the assessment approach itself.

4.2 LCM: IDENTIFY

4.2.1 Purpose Clarification and Intended Uses

Clarifying the purpose of applying the LCM approach helps to determine the extent of information and assessment required for the study. The "guiding questions", outlined in Chapter 2, are addressed as follows. In this research, the LCM approach is used to analyze a remedial option case study. As mentioned, the two main purposes of this study are to examine a site remediation process from a *life-cycle perspective* and to consequently assess and evaluate the LCM itself. Major concerns include: can a LCA-based approach be applied to contaminated site remediation issues and options; what are the environmental and human health impacts associated with the site remediation option; and does the consideration of issues through LCM highlight new issues associated with the remedial option?

The audience of this study is general, however, the details of the case study are confidential and consequently the raw data are not open to public review. The temporal boundary for this study is 25 years, allowing for inclusion of all potential impacts regardless of time dependency. As the contaminated site under consideration is in southern Ontario, the geographic boundary encompasses all activities occurring within the province of Ontario. The system boundary encompasses all remedial activities and is described in the following section.

4.2.2 Flow Diagrams

The case study site was used as a secondary lead smelting facility and formerly housed a coal gas storage facility. The site was extensively contaminated with lead, with lesser amounts of arsenic, cadmium and polyaromatic hydrocarbons (PAHs). The contaminated areas included buildings and paving, in addition to contaminated soil. All above-ground structures were decommissioned; the buildings on-site were first decontaminated, and then demolished and removed.

The soil remediation activities consisted predominantly of "excavation and disposal" of which a simplified process flow chart is given in Figure 4-1. The soil was excavated and sent to hazardous or non-hazardous waste sites according to the extent of contamination. The excavation pits were backfilled with clean fill as the remediation progressed. Water, including groundwater and surface water runoff from a dust mitigation program, was treated by coagulation followed by settling of the contaminated suspended particulates. The majority of the site was decommissioned to residential status; one lead-contaminated area was capped with asphalt and the access to a PAH-contaminated section was permanently restricted. This study's focus was on contaminated soil and groundwater remediation. Consequently, the decomissioning activities involving above-ground structures (i.e., buildings on-site) were not considered. These allocation issues are discussed later in this section. In Table 4-1, the remedial activities presented in the process flow diagram have been categorized according to life-cycle stages described in Chapter 2.

4.3 LCM: INFORM

4.3.1 Potential Impact Checklist

The purpose of the Potential Impact Checklist (Table 4-2), is to highlight potential impacts associated with the inventory items and with observations made. Many of the impacts listed in the Checklist have been highlighted as potential concerns (without "level of concern") as denoted by a check mark in Table 4-2. Some of these potential impacts will be subsequently addressed quantitatively in the LCA of the case study, focusing on the impacts of greatest priority to this case study, as discussed in the next section.

4.4 LCM: ASSESS

In *Assess*, an attempt was made to consider the information gathered thus far, highlight issues of interest or concern, and direct future study with the goal of assessing environmental and human health burdens. As outlined in Chapter 2, a LCA of a site remediation case study may be initiated at this point.

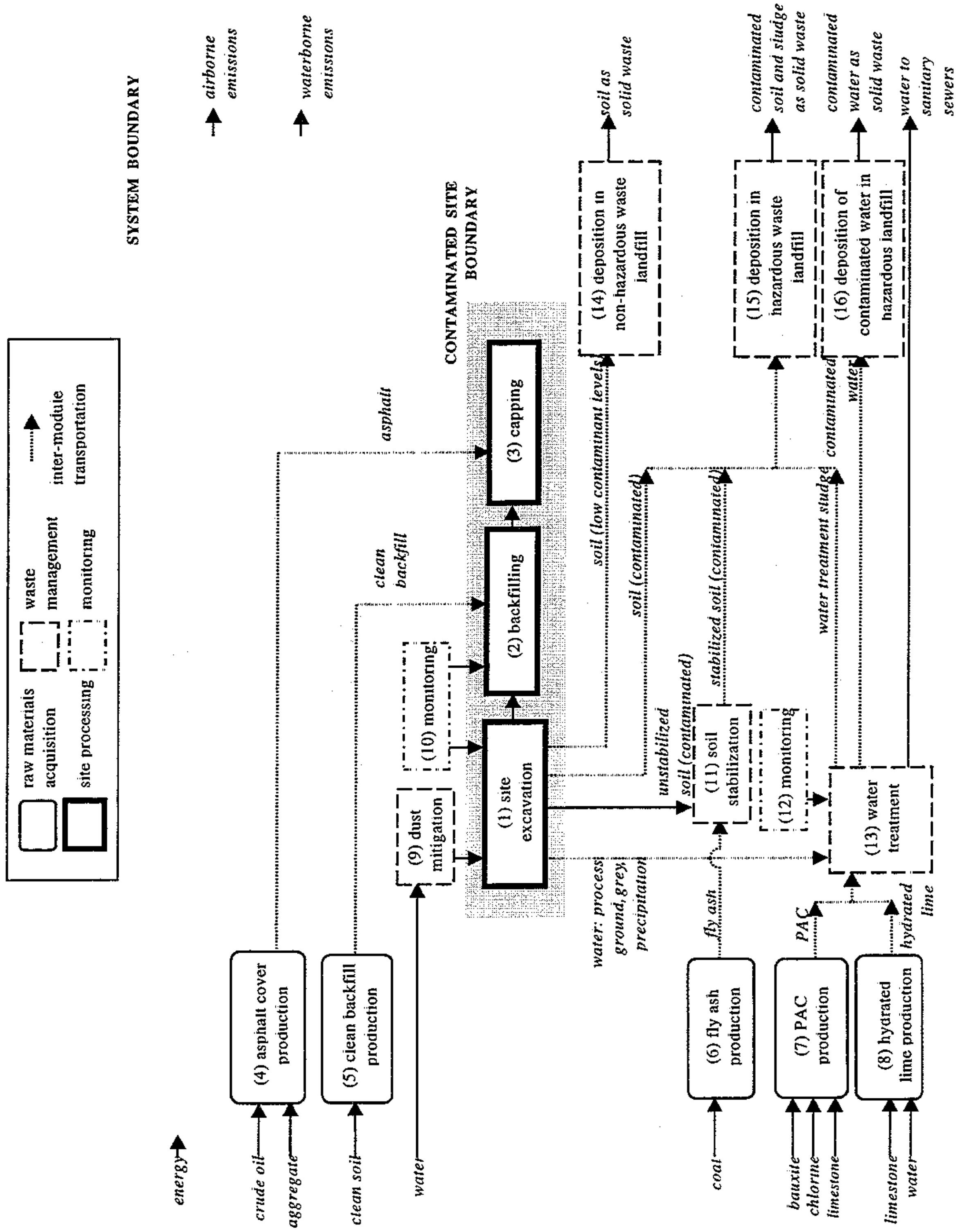


Figure 4-1 Basic process flow diagram for case study remedial activities

The activities have been numbered (1) through (16) and correspond to the inventory in Table 4-1. Transportation and monitoring activities have not been shown.

Table 4-1 Remedial and related activities categorized by inventory stage

Numbers correspond to activities shown in Figure 4-1.

Inventory Stage	*Remedial and Related Activities*
Raw Materials and Energy Acquisition	excavation of clean soil for backfill (5)
	energy (e.g., diesel fuel) acquisition
	production of fly ash (6)
	production of asphalt for capping (4)
	production of water treatment materials (aluminex, flocculant, etc.) (7, 8)
Site Processing	excavation of soil and groundwater (1)
	backfilling of excavation (2)
	capping of portion of site (3)
Waste Management	dust mitigation (9)
	soil stabilization (11)
	treatment of water (13)
	deposition of soil in hazardous landfill sites (15)
	deposition of soil in non-hazardous landfill sites (14)
	deposition of hazardous water in hazardous landfill sites (16)
Transportation / Distribution	transportation of soil to landfill sites
	transportation of waste water treatment sludge to landfill sites
	transportation of clean soil for backfill
	transportation of clean soil for site preparation
	transportation of secondary materials for water treatment
	transportation of asphalt for capping
	transportation of fly ash to site
	on-site excavation and backfilling activities
	distribution of groundwater and water from site to treatment process
Monitoring	initial ambient air monitoring on site
	continuous on-site monitoring of air (site excavation and backfilling) (10)
	intermittent monitoring of wastewater (12)
	post clean-up monitoring of soil, air, and groundwater
	long term monitoring at landfill sites

Table 4-2 Potential Impact Checklist for case study

Stressors	*Potential Impacts*	*Potential Concern*
	Pollution	
acid emissions (e.g., SO_2, HCl, NO_x, particulates)	→ acid rain	✓
greenhouse gases (e.g., CO_2, CFCs, methane, methyl chloride)	→ global warming	✓
ozone depleters (e.g., CFCs, CO, methyl furan, methyl chloride)	→ ozone depletion	✓
air polluters and photochemical fog (e.g., VOCs, semi-volatile compounds, PAHs, NO_x, SO_x, particulates)	→ air pollution	✓
nutrients (C, N, P)	→ eutrophication	
chemical changes to water quality (e.g., TSS)	→ stress on aquatic species	
chemical changes to soil quality (e.g., nutrient levels, organic content, pH)	→ soil quality disturbances	✓
toxic compounds in ground and surface water	→ groundwater impacts (ecotoxicity) → human health impairment (toxic effects)	✓
toxic compounds in soil	→ soil impacts (ecotoxicity) → human health impairment (toxic effects)	✓
toxic compounds and particulates in air	→ airborne transport to other media (ecotoxicity) → human health impairment (toxic effects)	✓
	Disturbance	
heat discharge	→ heat damage/dispersion of heat	
off-site land fragmentation	→ habitat alteration	✓
non-remediation of land	→ land stagnation	✓
construction, excavation	→ habitat destruction/ alteration	✓
compaction, paving, or application of an impervious soil coverage	→ effects on soil moisture, aquifer recharge, ecosystem regeneration	✓
changes to water quantity in aquifer	→ interrupted drainage, changes in aquifer level, change in stream base flow	✓
non-chemical soil quality changes (e.g., heating effects, soil particle size)	→ soil quality disturbances	✓
human social stressors (e.g., noise, dust, odour, vibration, aesthetic value, process heat)	→ human social disturbances	✓
	Depletion	
fossil fuel use/energy consumption	→ primary energy source depletion	✓
solid waste	→ land or space consumption	✓
water use	→ water consumption	✓
mineral use	→ mineral consumption	✓

For this case study, four main potential impacts associated with the excavation and disposal option have been highlighted, and include:

- impacts associated with off-site transportation emissions;
- land disturbances at the borrow pit and landfill sites (hazardous and non-hazardous);
- impacts associated with on-site excavation emissions (e.g., dust, water effluent); and
- impacts associated with post-remediation site quality (i.e., contaminants remaining on-site after remediation).

As appropriate for an initial application of the LCF, the relative quantitative importance of inventory or potential impacts have not been shown. Potential impacts, however, have been highlighted. To further explore these potential impacts, a LCA of the excavation and disposal case study is conducted and is the subject of the following sections.

4.5 LCA: INITIATION

The case study remediation activities have been described in the LCM *Identify* component. The process flow diagram has been given in Figure 4-1 and the life-cycle stages have been outlined in Table 4-1. In addition, the intended uses of this research have been described. Details regarding boundaries and data are given below.

4.5.1 Boundaries and Scope of Study

The life cycle begins with remediation activities. The duration of site remediation, from the beginning of soil excavation to final backfilling, was approximately 75 weeks, including a shut-down period. As discussed in Chapter 2, the time horizon chosen is approximately 25 years, which is intended to capture longer term effects that could arise from various disposal scenarios and allow for inclusion of potential impacts regardless of time dependency. Geographically, the contaminated site is located in southern Ontario, however the overall system boundary includes all related activities that occur within the southern Ontario region.

Activities occurring at the case study site extended beyond soil and groundwater remediation processes. The overall site clean-up included decontamination of the building surfaces, and the dismantling and demolition of the on-site building structures. The soil was then excavated, transported and deposited in hazardous and non-hazardous waste disposal sites. Activities performed concurrently included dust mitigation and water treatment. This study examines only soil and groundwater remediation processes and related activities, excluding the building decontamination and dismantling activities.

The scope of the study is limited to an investigation of specific stages of the site remediation life cycle, including: site processing, raw materials acquisition, waste treatment and transportation. We have not elaborated on post-site processing and monitoring activities due to their minor role overall. The study's scope is also limited in its assessment of potential impacts, focusing on the following potential impact indicators: Global Warming Potential (GWP), Gross Energy Requirement (GER), Solid Waste Burden (SWB), multi-media toxicity assessment for selected emissions, land use assessment, and an analysis of contaminants remaining on-site.

4.5.2 Data Issues, Assumptions and Peer Review

DATA SOURCES

For this study, the data were largely facility-specific, and not publicly accessible. Data were taken from consultants' reports, in particular from the final project completion report, and were collected over the duration of the actual site remediation. Personal communications with key individuals involved in the remediation project were an important source of data and expert opinion. Consequently, deviations or variations in data have not been smoothed out, as the data used are both process- and site-specific. Additional references, for data from secondary sources, are noted as appropriate.

MASS CONTRIBUTION ANALYSIS

An initial analysis of mass contribution [CSA 1994] was conducted to determine the relevance of the various material streams. This type of analysis revealed the materials considered negligible that are not considered further. The data for the total mass inputted were estimated from a preliminary data collection. These estimates of mass allow for calculation of the percentage of total input mass for each material stream. The results of the initial materials analysis are given in Table 4-3.

Table 4-3 Mass contribution of main process materials

Description of Material	*Total Mass Contribution (%)*
• hazardous soil	35.5
• non-hazardous soil	8.7
• groundwater, water for dust mitigation[1]	8.0
• clean fill for site preparation[2]	0.4
• calcium chloride[3]	-
• aluminex[4]	-
• hydrated lime[5]	-
• fly ash	0.2
• clean fill for backfill	47.2
• asphalt for cap[5]	-

[1] All water from the site, including groundwater, water used for dust mitigation, grey water, and rainfall was combined before treatment. Consequently, the total mass of all water was considered when calculating % of total mass contribution.
[2] The amount of clean fill deposited for site preparation was estimated to cover 5% of the total site area. Total site area was 3.7 acres (14 973 m^3) and the thickness of clean soil applied was approximately 0.3m. The density of the soil was estimated as 2400 kg/m^3 (from density of soil wetted and dried for 2 days).
[3] Amount of calcium chloride is considered to be negligible by contractor
[4,5] Unknown.

The analysis revealed that, on a mass basis, the system was dominated by the hazardous soil excavated (>35% of total mass contribution) and clean fill (>47% of total mass contribution). In addition to mass contribution, the degree of environmental relevance (e.g., toxicity) was used to guide data inclusion. For the case study, special consideration of lead was made because of its toxicity, in addition to its role as the major on-site contaminant.

FUNCTIONAL UNIT

As discussed in Chapter 2, difficulties arise when choosing a functional unit for an analysis of site remediation activities. Several alternatives exist, such as land area, volume or mass of treated soil, with the choice of functional unit largely dependent on the study's goal. For this non-comparative study, the data are presented on a "per site" basis.

ASSUMPTIONS

In this analysis, it was assumed that the activities took place in southern Ontario between 1992 and 1993. Consequently, secondary data sources (e.g., transportation emission factors) reflect the geographic specificity and time period. The consultants' reports and analyses were assumed to be complete and accurate.

Whereas an effort was made to determine the inventory items associated with all activities included within the flow diagram (Figure 4-1), the following were intentionally omitted due to their minor contribution or a lack of data: (i) PAC production (7) and consequently the inputs of bauxite, chlorine and limestone, with the associated emissions and energy consumption; (ii) emissions associated with capping (i.e., laying of asphalt) are addressed qualitatively only; and (iii) inputs and outputs, including energy use, associated with monitoring site excavation and backfilling (10), and water treatment (12). Monitoring methods included dustfall jars, hi-vol air particulate sampling (i.e., high volume blower draws air through a filter), mini-rams (i.e., portable, real-time monitoring of dust or fumes), lo-vols (i.e., low volume air samplers), and portable air monitors (i.e., PAMs). Though environmental releases from land disposal facilities may be included [SETAC 1991], emissions from hazardous and non-hazardous landfills have not been included due to a lack of appropriate data and an analysis of landfill emission records which suggests that emissions are minimal within the 25 year time span [Laidlaw 1994].

PEER REVIEW

The information contained within this paper has been subject to, and benefited from, peer reviews. Remediation experts and consultants associated with the case study examined the inventory data, LCA practitioners reviewed the modified LCA-based method, and toxicology experts critiqued the environmental and toxicity assessments.

4.6 LCA: INVENTORY

4.6.1 Introduction

The information presented below includes inventory data, sample calculations and data considerations (data source, data category, level of aggregation, and generation process). The inventory is first presented on a per module basis, and summaries of inventory items are then given for the following categories:

energy requirements: process-related, off-site transportation, on-site transportation

raw materials: clean soil, crude oil, aggregate, coal, limestone

water requirements: process water

waterborne emissions: raw materials acquisition, site processing, other (e.g., landfill considerations)

airborne emissions: raw materials acquisition, site processing, transportation-related, waste treatment, landfills

solid waste: hazardous soil, hazardous sludge, non-hazardous soil

water discharge: process water, groundwater, hazardous water

site quality indicators: on-site contaminants, area of remediated site

other information

As discussed in SETAC's *Life-Cycle Assessment Data Quality: A Conceptual Framework* [1994], it is important to have data quality information relating to data sources, data categories, levels of aggregation and generation processes. The following nomenclature, used throughout this section, describes the data quality information and is summarized below. The "data quality summary" is written as **(A/B/C/D)** with ratings for each category given below. To illustrate, if the data in question are historical, averaged, measured data from reference books and industry reports, the data quality summary would be **(1,5/3/2/1)**.

A. Data Sources
1. industry reports
2. laboratory test data
3. government documents
4. journals, books, patents
5. reference books
6. data bases
7. industry consultants
8. related LCIs/LCAs

***B.** Data Categories*
1. individual data
2. aggregated data
3. historical data
4. modelled data
5. encountered data
6. judgmental data

***C.** Level of Aggregation*
1. individual observations
2. averages (monthly, annual)
3. normalized (per unit values)

***D.** Generation Process*
1. actual measured
2. estimated/sampled
3. modelled/calculated
4. regulated

4.6.2 Process Flow Diagrams

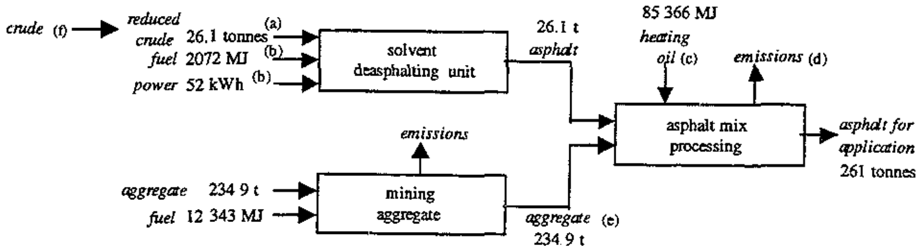
"Excavation and disposal" processes and related activities are shown in a simplified process flow chart (Figure 4-1); the numerical references in the text refer to the numbered flow chart modules. The remedial activities presented in the process flow diagram have been identified according to life-cycle stages described. The contaminated site boundary and the overall system boundary have been highlighted, illustrating how this assessment broadens consideration of activities beyond the contaminated site itself.

The main remediation activities were soil excavation (1) and transportation to hazardous (15) or non-hazardous (14) waste sites according to the extent of contamination. A small portion of the hazardous soil was first combined with fly ash (6) to stabilize the soil for transportation (11) and subsequent deposition in a hazardous landfill (15). The excavation pits were backfilled (2) with clean backfill (5) as the remediation progressed. During excavation, a dust mitigation program was in effect (9). Water, including groundwater and surface water runoff from a dust mitigation program, was treated by coagulation followed by settling of the contaminated suspended particulates (13). The water treatment chemicals used included hydrated lime (8) and poly aluminum chloride, or PAC (7). Highly contaminated water was removed to a hazardous landfill (16) as was the water treatment sludge (15). Most of the site was decommissioned to residential status, one lead-contaminated area was capped (3) with asphalt (4), and access to a PAH-contaminated section was permanently restricted. Air emissions were monitored during site excavation and backfilling (10), and contaminant levels in the water treatment system (13) were measured.

4.6.3 Raw Materials: Asphalt Cover Production (4)

DESCRIPTION OF PRODUCTION

The production of asphalt cover involves the following processes: production of asphalt from crude oil; excavation of aggregate; and preparation of asphalt mix. These processes are illustrated below.



(a) allocation based on mass (represents 18wt% reduced crude to asphalt)
(b) fuel use allocation based on mass; utility estimates from Handbook of Petroleum Refining Processes (1996), p 10.42
(c) heating oil is used in the production of asphalt mixes; estimates from Ullmann's Encyclopedia (1985), volA3 p 186
(d) emissions based on heating oil combustion
(e) aggregate amount based on 10wt% binder content; estimates from Ullmann s Encyclopedia (1985), volA3, p 184
(f) the reduced crude (vacuum residuum) depends largely on the amount of asphalt in the crude oil. 30vol% yield on crude may be estimated [Kirk-Othmer (1992) vol. 3 p 692-693], however allocation issues arise.

ASPHALT COVER REQUIREMENT

An asphalt cover, thickness 50 mm[1], was applied to a portion of the site for capping purposes. The density of this cover was estimated as 2090 kg/m^3 (i.e., asphalt [Kirk-Othmer 1978] and dry packed aggregate [Perry's 1984]). The area of asphalt cover was 2500 m^2. The mass of asphalt cover used on-site was 261 tonnes. The data quality summary is **(1,5/2/1/2,3).**

Calculation of Asphalt Required for Cover

mass of asphalt cover

= area of cover × thickness of cover × density of cover

= 2500 m^2 × 0.05 m × 2090 kg/m^3

= 261 tonnes

INPUTS AND OUTPUTS

Crude oil and aggregate. Asphalt compacted mixes that are used for paving (e.g., roads, parking areas, etc.) are composed of bitumen binder (4-10 wt%) mixed with mineral aggregates [Ullmann's 1985]. This mixing is carried out between 150 and 160°C, after which the mix is transported to the site. Asphalts, a term used synonymously with bitumens, are produced from the refining of petroleum. Crude oils have varying asphalt contents, and the process of producing an asphalt product depends on this content. Crude oils containing low asphalt content (i.e., <15%) are used to produce asphalt by means of a propane deasphalting and fractionation process involving the precipitation of asphalt from a residuum stock by treatment with propane under controlled conditions.

For the site, if we assume 10 wt%, a total of 261 tonnes of asphalt cover mix was required, consisting of 26 tonnes of asphalt (bitumen binder) and 235 tonnes of mineral aggregates. Since asphalt comes from processing crude oil (crude to reduced crude to asphalt), many other valuable products are produced from the initial crude oil. We assumed that a component (mass basis) of the initial crude oil goes directly to producing the asphalt, therefore 26 tonnes of crude oil was allocated for the production of the 26

---

[1] Completion report. 1994.

tonnes of asphalt required [Henshaw 1994].

Energy. Energy used in asphalt production stems from: (i) production of asphalt from crude oil; (ii) mining of mineral aggregates; and (iii) preparation of asphalt mixes with the addition of mineral aggregates.

(i) The amount of asphalt available from crude oil depends largely on the amount of residuum. Because crude is used to produce many products, we allocated the amount of crude residuum and crude oil on a mass basis [Henshaw 1994]. Based on utility estimates, to process the reduced crude into 18 wt% asphalt (the remainder being deasphalted oil, DAO) we required 11 510 MJ of natural gas (6% or 124.3 MJ precombustion energy), and 287 kWh of power [Handbook of Petroleum Refining Processes 1996].

(ii) To obtain the 235 tonnes of mineral aggregates required for the asphalt mix, we used the following estimates based on the energy requirements for mining backfill, with correction for mass:

aggregate mining extraction energy (diesel) requirements = 11 145 + 290 + 897

= 12 332 MJ

Other energy associated with precombustion processes was estimated at 11% (diesel precombustion), bringing the total energy required to 13 701 MJ.

(iii) Preparation of 1 tonne of asphalt mix (i.e., aggregate-bitumen) requires approximately 9 L of heating oil during processing [Ullmann's 1985]. To produce 261 tonnes of asphalt mix, we required 2349 L of heating oil (85 257 MJ). 9390 MJ of precombustion (other) energy was consumed.

Emissions. Emissions stem from two main activities: (i) processing of asphalt mix; and (ii) aggregate mining. Data concerning emissions associated with asphalt application at the site were not found, though the release of carbon monoxide, nitrogen dioxide, sulfur dioxide, hydrogen sulfide, phenols, ozone, hydrocarbons, and particulate matter may be associated with hot-mix asphalts.

(i) Solvent Deasphalting and Asphalt mix processing

Fuel and electricity are used in asphalt production. The following are emissions from precombustion of fuel (assuming natural gas), and the production and delivery of electricity (using a mix representative in Ontario: 32% hydro, 45% nuclear, 23% coal). These emissions also come from the use of heating oil, both precombustion and combustion.

Table 4-4 Emissions associated with asphalt processing and asphalt mixing

Emissions	*Quantities* (kg)	
Air	*Precombustion*	*Combustion*
CO_2	642	59 640
NO_x	6.2	66.5
CO	0.2	1.9
CH_4	6.0	14.3
particulates		NA
Solid Waste		
mineral waste	41.3	
ash	7.0	
inert chemicals and industrial waste	3.0	

(ii) Aggregate mining

These emissions come from transportation activities where the aggregate is mined at the site (i.e., does not include transportation between quarry and contaminated site).

Table 4-5 Emissions associated with aggregate mining

Emissions	*Quantities* (kg)	
	Precombustion	*Combustion*
Air		
CO_2	76.8	871
VOC	NA	2.1
CH_4	0.8	0.06
NO_x	0.8	9.8
N_2O	NA	0.13
SO_2	NA	2.8
CO	0.02	25.2
particulates	NA	1.0
Solid Waste		
mineral waste	0.6	
ash	0.7	
inert chemicals and industrial waste	0.1	

SUMMARY

Table 4-6 Summary for asphalt cover production

Inputs		*Outputs*	
crude oil	26 tonnes	asphalt mix for cover	261 tonnes
aggregate	235 tonnes	*airborne emissions:*	
		CO_2	61 200 kg
energy:		CO	27.3 kg
coal	757 MJ	NO_x	83 kg
diesel	12 300 MJ	particulates	1.0 kg
oil	85 400 MJ	N_2O	0.13 kg
hydro	332 MJ	CH_4	21.2 kg
natural gas	11 400 MJ	SO_2	2.8 kg
nuclear	1 530 MJ	VOC	2.1 kg
precombustion	11 400 MJ		
		solid waste:	
		mineral waste	41.9 kg
		ash	9.8 kg
		inert chemicals and industrial waste	5.1 kg
		drillings and cuttings	36.3 kg

4.6.4 Raw Materials: Clean Backfill Production (5)

DESCRIPTION OF PRODUCTION

Backfill material was excavated from a sand and gravel pit. This material was analyzed for lead (<5 ppm to 12 ppm), arsenic (<0.1 ppm to 0.6 ppm) and cadmium (<0.5 ppm to 1.4 ppm). Transportation at the quarry was the main activity involved in clean backfill acquisition.

CLEAN BACKFILL REQUIREMENT

The number of loads of clean soil brought on-site were noted, and the total mass was calculated using densities from the soil analysis reports. The mass of clean backfill brought on-site was 67 539 tonnes. The data quality summary is **(2/1/1/1,3)**.

INPUTS AND OUTPUTS

Energy. Energy is consumed when mining clean backfill aggregate. Estimates of the amount of energy used for the following came from the energy requirement calculated for on-site transportation of the same material: (i) dig the aggregate; (ii) move the aggregate on-site; and (iii) load it onto trucks.

Calculation of Backfill Extraction Energy Requirements

backfill extraction energy requirements = energy consumed by backhoe + energy consumed by bulldozer + energy consumed by loader

= 3 203 214 MJ + 83 200 MJ + 257 921 MJ

= 3 544 335 MJ

Emissions. These emissions stem from on-site transportation activities at the backfill source.

Table 4-7 Emissions associated with backfill production

Emissions	*Quantities (kg)*	
	Precombustion	*Combustion*
Air		
CO_2	22 000	250 100
VOC	NA	613
CH_4	228	18
NO_x	228	2800
N_2O	NA	37
SO_2	NA	797
C_xH_y	228	
CO	6.3	7230
particulates	NA	283
Solid Waste		
mineral waste	173	
ash	197	
inert chemicals and industrial waste	38	

SUMMARY

Table 4-8 Summary for clean backfill production

Inputs		*Outputs*	
clean soil	67 540 tonnes	*on-site transportation air emissions:*	
		CO_2	272 200 kg
		VOC	613 kg
		CH_4	247 kg
		N_2O	37 kg
on-site transportation energy (diesel)	3 544 000 MJ	NO_x	3032 kg
		SO_2	797 kg
		CO	7236 kg
		particulates	283 kg
		clean soil	67 540 tonnes
		mineral waste	173 kg
		ash	197 kg
		inert chemicals and industrial waste	38 kg

4.6.5 Raw Materials: Fly Ash Production (6)

DESCRIPTION OF PRODUCTION

Fly ash is a by-product of coal combustion, an energy generating process, and is collected by electrostatic precipitators on flue stacks. The ash is used to stabilize some contaminated soil. The fly ash originated from a local utility and was supplied by a company dealing in fly ash. The principal constituents are silicates and alumino-silicates, where 3% is free silica with a respirable fraction of less than 1%. Trace metal content was not available.

FLY ASH REQUIREMENT

Overall, 300 tonnes of fly ash was brought on-site. The data quality summary is **(1/1/1/2)**.

INPUTS AND OUTPUTS

Coal. 0.073 tonnes of fly ash is produced per tonne of coal (based on 98% precipitator efficiency, 86% ash in gas, 12% carbon ash)[2]. Similarly to asphalt binder, fly ash is produced along with many other products. The major "product" from coal used at a generating station is energy; fly ash is precipitated out of the flue gas [Perry's 1984]. Therefore, the total amount of coal necessary (i.e., 4110 tonnes) to produce 300 tonnes of fly ash is not considered; rather, the equivalent amount of coal (i.e., 300 tonnes) is used in our analysis [Henshaw 1994]. ?

Energy. Energy consumed in the process of electrostatic precipitation was not determined and is assumed to be zero.

Emissions. Emissions from fly ash production are not considered, according to the zero-allocation assumption.

SUMMARY

Table 4-9 Summary for fly ash production

Inputs		*Outputs*	
coal	300 tonnes	fly ash	300 tonnes
energy	neglected	emissions	neglected

---

[2] Arnold, J. 1997. Ontario Hydro, pers. comm.

4.6.6 Poly Aluminum Chloride (PAC) Production (7)

PAC REQUIREMENT

On-site, two 45 gallon barrels of PAC were used for wastewater treatment[3]. PAC is a proprietary agent used for flocculation. Its approximate empirical formula is $Al(OH)_{1.5}(SO_4)_{0.125}Cl_{1.25}$ and it is available as a solution with an aluminum content of 10 wt% expressed as Al_2O_3 [Kirk-Othmer 1978]. PAC is produced from a mix of aluminum chloride neutralized using calcium carbonate, and an organic coagulant (cationic)[4].

Calculation of PAC Requirement

Given that 45 US gallons = 170 kg H_2O, the solution weighs 170 kg/0.9 (i.e., 188 kg), the weight of PAC is 18.9 kg/barrel. Overall, it was estimated that 37.6 kg of PAC was used on-site.

Due to a lack of detailed information on PAC formation, PAC was not considered in the inventory.

4.6.7 Raw Materials: Hydrated Lime Production (8)

DESCRIPTION OF PRODUCTION

Limestone (crushed/broken) is obtained by open-pit quarrying. Lime (CaO) is then produced from limestone through calcination in rotary and vertical kilns.

$$CaCO_3 \rightarrow CaO + CO_2 \text{ (off gas)}$$

The heat required includes sensible heat to raise the rock to decomposition temperature, and latent heat of decomposition [Encyclopedia of Chemical Processing and Design 1988]. Practical considerations require heating the rock to 1200-1300°C, making the theoretical heat requirements 4 250 000 Btu/ton lime [Encyclopedia of Chemical Processing and Design 1988]. Note: 4 250 000 Btu/ton lime × 1055.06 J/Btu × 1 MJ/1 000 000 J × 1 ton/1000 kg = 4.5 MJ/kg. Slaking or hydrating the lime is as

follows. Water is added to lime in amounts to balance the heat evolved. 3

$$CaO + H_2O \longrightarrow Ca(OH)_2$$

HYDRATED LIME REQUIREMENT

Lime is used to treat all the wastewater. It is used to raise the pH of water, which prevents heavy metals from solubilizing and neutralizes acidic water. It counteracts the increase in non-carbonate hardness in the wastewater, caused by alum addition, and has a dispersing effect. It is commonly used as a co-flocculant [Kirk-Othmer 1978]. For wastewater with low contaminant levels, hydrated (or slaked) lime was used alone for treatment.

According to consultants' estimates, 40 bags (20 kg) of hydrated lime were used on-site for water treatment. The total amount of hydrated lime used was, therefore, 800 kg.

INPUTS AND OUTPUTS

Raw materials and energy. Limestone is first mined (1081 kg) from which lime (605.4 kg of CaO) is produced. To produce 800 kg of hydrated lime ($Ca(OH)_2$), water (194.6 kg) is added to the lime at temperatures ranging from 82 to 99°C [Goldfarb et al. 1984]. The slaking reaction time varies between 10 minutes (highly reactive limes) to 30 minutes (low reactivity) [Goldfarb et al. 1984]. Hydrated lime is suitable for either dry feeding or slurrying. Energy associated with hydrated lime production involves: (i) limestone extraction; and (ii) lime production.

Table 4-10 Energy for limestone mining

Energy	*Amount*
natural gas	14.1 MJ
diesel	22.7 MJ
crude oil (transportation)	75.7 MJ
electricity	3.9 kWh

Table 4-11 Energy for lime production

Energy	*Amount*
natural gas	1.4 MJ
coal	1.4 MJ
electricity	16.9 kWh

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[3] MacDonald, I. 1997, pers. comm.

[4] Underwood, K. 1997, pers. comm.

Emissions. Airborne emissions are associated with limestone mining and the production of lime (CaO). For the production of 800 kg of hydrated lime, the emissions from limestone mining, lime production and slaking of the lime are given in Tables 4-12 and 4-13.

Table 4-12 Airborne emissions for limestone mining

Emissions	*Amount* (kg)
CH_4	1.1E-02
NO_x	2.2E-02
NO_2	3.1E-02
CO	2.0E-03
particulates	2.0E-03
CO_2	19.6

Table 4-13 Airborne emissions for lime production

Emissions	*Amount* (kg)
CO	1.27E-03
NO_x	1.13E-02
CH_4	1.23E-02
CO_2	4.2

Air and solid waste emissions associated with precombustion energy are incorporated in the final table.

SUMMARY

Table 4-14 Summary for lime production

Inputs		*Outputs*	
		hydrated lime	800 kg
limestone	1081 kg		
water	194.6 kg		
		airborne emissions:	
natural gas	15.5 MJ	NO_x	0.07 kg
diesel	22.7 MJ	N_2O	0.04 kg
crude oil	75.7 MJ	CO	0.008 kg
electricity	20.8 kWh	particulates	0.002 kg
coal	56.6 MJ	CO_2	512 kg
nuclear	111.4 MJ	CH_4	1.5 kg
hydro	24.3 MJ		
precombustion	11.8 MJ		
		solid waste:	
		mineral waste	0.25 kg
		ash	0.01 kg
		inert chemicals and industrial waste	0.00 kg

4.6.8 Energy Acquisition

Various types of energy were used, including diesel fuel, furnace oil and electricity. All energy use was recorded according to the activity and the additional energy requirement associated with energy production was added. This is applied to most of the activities considered, and was included within each as appropriate.

4.6.9 Site Processing: Site Excavation (1)

PROCESS DESCRIPTION

The site was excavated zone-by-zone using a track-mounted backhoe. The energy consuming processes occurring on-site were all transportation-related, with diesel fuel as the energy source. On-site, several different vehicle types were used, including a track mounted backhoe, bulldozer, and loader. Overall, the excavation took 75 weeks, including a stop-work period due to inclement weather and while plans were modified.

Most of the contaminated soil was removed from the site, with contaminants remaining in two of the five zones.

INPUTS AND OUTPUTS

Energy. Estimates were obtained from a consultant closely involved with the remediation project, concerning the types and number of vehicles used, the approximate number of hours operated, and fuel consumption. Transportation consumption was then calculated from these fuel consumption estimates. The data quality summary is **(7,1,4/1,6/1,2/2,3)**.

Sample Calculation

The amount of transportation energy consumed, in MJ, is given by:

transportation energy consumed (MJ) = rate of diesel consumed × number of vehicles × number of days operated × energy content of diesel fuel[5].

---

[5] Gross energy content factor for diesel fuel is 38.68 MJ/L (or 38.68 GJ/m^3) [NEB 1994].

To illustrate the calculation, the amount of transportation energy consumed for one full-time backhoe working for 160 working days with a diesel fuel consumption of 350 L/vehicle/day is:

$$\text{transportation energy consumed} = 350\ \frac{\text{L}}{\text{vehicle}\cdot\text{day}} \times 1$$

$$\text{vehicle} \times 160\ \text{days} \times 38.68\ \frac{\text{MJ}}{\text{L}} = 2\ 166\ 080\ \text{MJ}$$

Table 4-15 Summary of energy requirements for excavation

On-Site Equipment	*Rate of Diesel Consumption* [(a)] (L/vehicle/day)	*Number of Vehicles*[(a)]	*Number of Vehicle Days*[(a)] (days)	*Volume of Fuel Consumed* (L)	*Transportation Energy Requirement* (MJ)
backhoe	350	1	160	56000	2 166 080
backhoe	350	2	30	21000	812280
bulldozer	50	1	40	2000	77 360
loader	155	1	40	6200	239 816
				total:	3658045
				transportation energy:	3295536
				other energy:	362509

(a) MacDonald, 1996, pers comm

The amount of energy consumed was calculated according to the gross energy content of diesel fuel, without accounting for energy used to bring the fuel to market, i.e., energy is consumed by processing crude oil, piping the crude oil to the refinery, refining and then transporting the diesel to the consumer. An overall efficiency of diesel fuel delivered to the vehicle has been estimated as 89% [Covery et al. 1976]. Alternatively, energy conversion factors sometimes include an 11% addition for crude transportation and refining, which may be added to "other energy" figures [Cowell 1993].

Airborne emissions. The process-related airborne emissions (i.e., emissions generated on-site) that were measured included total dustfall and lead deposition. Lead-contaminated dust emissions were a concern during site remediation and, consequently, dustfall sampling was conducted throughout the remediation activities. Total dustfall and lead concentrations in the dust were analyzed monthly. It was assumed that the dust falling on-site was representative of off-site emissions. The total amount of particulates and lead emitted during the project was 1391 kg dust, containing 3.57 kg of lead.

Transportation emissions were calculated using emission factors appropriate for the type of vehicle, loading, and fuel type. Typical emission factors for trucks using diesel fuel are given in Table 4-29. The emissions associated with on-site transportation activities for excavation are given in Table 4-16.

Sample Calculation

VOC emissions for a loader are:

= 0.173 g/MJ × 239 816 MJ = 41 488 g or 41.5 kg

Table 4-16 Summary of airborne emissions associated with on-site transportation activities of excavation.

	Emissions (kg)							
On-Site Operation of:	*CO_2*	*VOC*	*CH_4*	*N_2O*	*particulates*	*CO*	*SO_2*	*NO_x*
backhoe	152 880	375	11.2	22.4	173	4419	487	1713
backhoe	57330	140.5	4.2	8.4	65	1657	183	643
bulldozer	5 460	13.5	0.4	0.8	6	158	18	61
loader	16 926	41	1.2	2.5	19	489	54	190
total:	232596	570.1	17.0	34.1	264	6723	742	2607

Solid waste. The "hazardous" soil was sent to hazardous landfill sites for disposal. The total amount sent was 50 380 tonnes, or approximately 21 000 m^3 of uncompressed soil[6]. The data quality summary is **(1/2/1/2)**.

Some of the soil excavated was non-hazardous according to the chemical analysis, and was consequently sent to a non-hazardous facility. The total amount of non-hazardous soil sent to landfill was 12 418 tonnes. The data quality summary is **(1/2/1/2)**.

---

[6] A specific gravity of 2400 kg/m^3 was assumed. This is an estimated density that would be expected from the addition of water for dust control

SUMMARY

Table 4-17 Summary for site excavation

Inputs		*Outputs*	
Energy		*Airborne emissions:*	
diesel	3 295 500 MJ	dust	1391 kg
precombustion	362 500MJ	lead	3.57 kg
		Transportation-related air emissions:	
		CO_2	253100 kg
		VOC	570 kg
		CH_4	230 kg
		N_2O	34 kg
		NO_x	2820 kg
		SO_2	741 kg
		CO	6730 kg
		particulates	264 kg
		mineral waste	161 kg
		ash	183 kg
		inert chemicals	35 kg

4.6.10 Site Processing: Backfilling (2)

PROCESS DESCRIPTION

The backfill was applied to the site via on-site transportation activities, and diesel fuel was used as the energy source. On-site, several different vehicle types were used, including a track mounted backhoe, bulldozer, and vibratory compactor.

INPUTS AND OUTPUTS

Energy. As for excavation (1), estimates were obtained from a consultant concerning the types of vehicles used, the approximate number of hours operated, the number of vehicles used throughout the remediation, and fuel consumption. From the fuel consumption, the associated transportation consumption values were calculated. The data quality summary is **(7,1,4/1,6/1,2/2,3)**.

Sample Calculation

The amount of transportation energy consumed, in MJ, is given by:

transportation energy consumed (MJ) = rate of diesel consumed × number of vehicles × number of days operated × energy content of diesel fuel[7].

To illustrate, the amount of transportation energy consumed by a vibratory compactor used a total of 80 working days with a diesel fuel consumption of 25 L/vehicle/day is:

$$\text{transportation energy consumed} = 25\,\frac{\text{L}}{\text{vehicle day}} \times 1\text{ vehicle} \times 80\text{ days} \times 38.68\,\frac{\text{MJ}}{\text{L}}$$

= 77 360 MJ.

Table 4-18 Summary of energy requirements for backfilling

On-Site Equipment	*Rate of Diesel Consumption* [(a)] (L/vehicle/day)	*Number of Vehicles*[(a)]	*Number of Vehicle Days*[(a)] (days)	*Volume of Fuel Consumed* (L)	*Transportation Energy Requirement* (MJ)
bulldozer	50	1	40	2000	77 360
vibratory compactor	25	1	80	2000	77 360
				total:	171 739
				transportation energy:	154 720
				other energy:	17 019

(a) MacDonald, 1996

The amount of additional energy (i.e., *other energy*) associated with on-site transportation, calculated as 11% of the total transportation energy consumed, was 17 019 MJ.

Emissions. On-site transportation emissions for backfilling were calculated similarly to those for excavation, using emission factors described in Section 4.6.19.

Sample Calculation

VOC emissions for a loader are:

= 0.173 g/MJ × 239 816 MJ = 41 488 g = 41.5 kg

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[7] Gross energy content factor for diesel fuel is 38.68 MJ/L (or 38.68 GJ/m^3) [NEB 1994].

Table 4-19 Summary of airborne emissions associated with on-site transportation activities for backfilling (not including precombustion emissions)

	Emissions (kg)							
On-Site Operation of:	*CO_2*	*VOC*	*CH_4*	*N_2O*	*particulates*	*CO*	*SO_2*	*NO_x*
bulldozer	5 460	13.5	0.4	0.8	6	158	18	61.2
vibratory compactor	5 460	13.5	0.4	0.8	6	158	18	61.2
total:	10920	27	0.8	1.6	12	316	36	122.4

SUMMARY

Table 4-20 Summary for backfilling

Inputs		*Outputs*	
clean soil	67 539 tonnes	*Transportation-related air emissions:*	
		CO_2	11 880 kg
		VOC	27 kg
		CH_4	11 kg
		N_2O	1.6 kg
		NO_x	132 kg
energy for on-site activities:		SO_2	34 kg
diesel	154 720 MJ	CO	316 kg
precombustion	17 019 MJ	particulates	12 kg

4.6.11 Site Processing: Capping (3)

PROCESS DESCRIPTION

Clean backfill (included in Backfilling) and asphalt was deposited over approximately 2500 m^2 of the site.

INPUTS AND OUTPUTS

Emissions from asphalt application are known to contain benzene, PAHs, lead, total and PM10 particulate, CO, and SO_2 [Ullmann's 1985, U.S. EPA 1994]. Due to a lack of data, however, these emissions have not been quantified.

SUMMARY

Table 4-21 Summary for capping

Inputs		*Outputs*	
asphalt mix	261 tonnes	asphalt laying emissions	not included

4.6.12 Post-Site Processing

Maintenance may occur within the 25 year time frame, and require removal and re-application of the cap, or simply re-application of the cap. We have not included this or other post-site processing activities due to a lack of data.

4.6.13 Waste Management: Water Treatment (13)

PROCESS DESCRIPTION

The water treatment system was designed to treat the groundwater and process water from dust mitigation, in addition to surface water runoff, and grey water from showers and laundry use. All the water was collected from the excavation pits and sumps, and was transferred using portable pumps to a storage tank. The two water treatment methods used depended upon the extent of contamination: (i) water with high concentrations of metals or organic contaminants was treated with an inorganic flocculent (poly aluminum chloride, PAC), followed by hydrated lime to raise pH and promote flocculation and settling; and (ii) water with lower contaminant concentrations was treated with hydrated lime alone. After the addition of these water treatment chemicals, settling was allowed and the treated water was discharged to a sanitary sewer.

INPUTS AND OUTPUTS

Emissions in process water were calculated from data on volumes of water discharged on particular dates and corresponding chemical analyses for various discharge batches. The discharge batch was correlated with the analysis for the closest analysis date prior to the discharge date. The discharge volumes were given in m^3 and the contaminant concentrations were given in mg/L. The data quality summary is **(1,2/1/1/1)**.

The total mass of each contaminant (abbreviated as "cont.") emitted is calculated as follows:

$$\text{cont. [kg]} = \text{cont. concentration } [\frac{\text{mg}}{\text{L}}] \times \text{volume } [\text{m}^3] \times \frac{1000\text{ L}}{\text{m}^3} \times \frac{1\text{ g}}{1000\text{ mg}} \times \frac{1\text{ kg}}{1000\text{ g}}$$

$$= \frac{\text{concentration } [\frac{\text{mg}}{\text{L}}] \times \text{volume } [\text{m}^3]}{1000} \text{ [kg]}$$

A summary of the contaminants emitted in the treated wastewater is given in Table 4-22, and a sample calculation is given below.

Sample Calculation

For discharge batch number 9, the volume was 60.63 m^3 and the corresponding analysis indicated 1.99 mg of Pb/L. The mass discharged was calculated as:

$$\text{mass of Pb for discharge batch number 9} = 1.99 \frac{\text{mg}}{\text{L}} \times 60.63 \text{ m}^3$$

$$= 121 \text{ g} = 0.121 \text{ kg}$$

The total amount of lead discharged was then calculated by summing the individual batch discharge amounts.

Table 4-22 Amounts of various contaminants emitted in wastewater.

Contaminants Measured in Wastewater	*Total Mass Emitted (kg)*
Fluorine	4.5
Silver	0.05
Aluminum	116
Arsenic	5.8
Cadmium	1.6
Chromium	0.4
Copper	13.5
Iron	550
Lead	91
Phosphorus	6.1
Zinc	13
BOD	60
TSS	4 525

Hazardous sludge was generated from the wastewater treatment facility. The total amount of sludge sent to the hazardous landfill was 95 tonnes.

As discussed above, process water, groundwater, grey water (e.g., laundry and showers) and precipitation were combined, treated, and discharged together. It was

estimated that groundwater represents 70% of the total water treated. Therefore, the total amount of process water discharged from the site would be approximately 3430 m^3 (3429.28 m^3). The amount of groundwater taken from the site and discharged was approximately 8000 m^3 (8001.7 m^3). The data quality summary is **(1/2/2/2)**.

Contaminated water, which was considered to be "untreatable" according to the capabilities of the on-site water treatment facilities, was transferred to a hazardous disposal facility. The data quality summary is **(1/1/1/1)**.

Total amount of water "consumed" was 108 tonnes, which was sent to a hazardous landfill site.

SUMMARY

Table 4-23 Summary for wastewater treatment

Inputs		*Outputs*	
contaminated water	11 431 m^3	water treatment sludge	95 tonnes
PAC	not included	contaminated water	108 tonnes
hydrated lime	800 kg	water to sanitary sewers	11 431 m^3
		waterborne emissions to sanitary sewers	See Table 4-22

4.6.14 Waste Management: Dust Mitigation (9)

PROCESS DESCRIPTION

Dust was suppressed by spraying process water over the site. Groundwater, grey water (e.g., laundry and showers) and precipitation were combined with the process water on-site, treated, and discharged.

WATER REQUIREMENTS

As noted above, water was used for a variety of purposes, some of which were outside the process boundary (e.g., for decommissioning buildings). Data were available on total water discharged. Thus, it was not possible to disaggregate water use according to life-cycle stage, nor was it possible to estimate the amount of water evaporated from the site.

Thus, it was assumed that the total amount of water discharged was equal to the total amount of water used plus the groundwater taken from the site.

INPUTS AND OUTPUTS

The total amount of process water added was approximately 3430 m^3 (3429.279 m^3). The data quality summary is **(1/2/2/2)**.

SUMMARY

Table 4-24 Summary for dust mitigation

Inputs		*Outputs*	
water	3430 m^3	water emitted	3430 m^3

4.6.15 Waste Management: Soil Stabilization (11)

PROCESS DESCRIPTION

A portion of the soil excavated from the site required stabilization with fly ash before transportation and subsequent disposal at a hazardous waste facility.

INPUTS AND OUTPUTS

Whereas it was known how much fly ash was brought on-site, it was not known how much soil was stabilized. The fly ash and stabilized soil were combined with other hazardous soil from the site for subsequent transportation off-site.

SUMMARY

Table 4-25 Summary for soil stabilization

Inputs		*Outputs*	
fly ash	300 tonnes	fly ash and hazardous soil	total amount unknown: combined with other contaminated soil for disposal
unstabilized soil (contaminated)	unknown		

4.6.16 Waste Management: Deposition of Soil in Non-Hazardous Landfill (14)

PROCESS DESCRIPTION

While the disposal of the soil is important from a life-cycle perspective, it is difficult to choose an appropriate system boundary, i.e., to determine the extent of analysis required. For example, do we consider the landfill preparation stage involving the activities required in advance of deposition of hazardous and non-hazardous soil in the excavation trenches? Do we consider the energy expended in the excavation of the trenches, the capping of the site, etc.? For simplification purposes, the amount of solid waste added to the landfill is noted. In addition, the use of landfill contributes to the use of land outside of the contaminated site itself. This disturbance was qualitatively addressed in Section 4.6.23 and Table 4-35.

INPUTS AND OUTPUTS

Solid waste. Approximately 12 400 tonnes of the soil excavated from the site was considered "non-hazardous" according to the chemical analysis, and sent to a non-hazardous facility. The data quality summary is **(1/2/1/2)**.

Emissions. The non-hazardous soil deposited in landfill was used primarily for cover. We assumed that emissions from the landfill were minimal, e.g., dust evolved from the soil was assumed to be re-deposited on-site. Leachate attributed to the contaminated soil was difficult to determine and consequently was neglected.

SUMMARY

Table 4-26 Summary for deposition of soil in non-hazardous landfill

Inputs		*Outputs*	
non-hazardous soil	12 418 tonnes	soil as solid waste (non-hazardous)	12 418 tonnes

4.6.17 Waste Management: Deposition of Soil in Hazardous Landfill (15)

PROCESS DESCRIPTION

Soil deemed hazardous due to elevated lead and cadmium concentrations, was discarded in a hazardous landfill site. Note that whereas the term "soil" is used throughout, the soil may have contained a high percentage of crushed battery casings, bricks or unidentified granular material since the site was a former secondary lead smelting facility

INPUTS AND OUTPUTS

Solid waste. The total amount of hazardous soil as solid waste was 50 380 tonnes, or approximately 21 000 m^3 of uncompressed soil[8]. Water treatment sludge (95 tonnes) was also discarded. The data quality summary is **(1/2/1/2)**.

The existing landfill covered 35.3 acres. Each landfill cell was approximately 18.3 m deep and 150 m wide, and was excavated in a series of lifts at 6.1 m per lift; approximately 12.2 m (height) of waste was deposited in each cell. Therefore, the maximum total volume of waste in the landfill, according to the current landfill design, was approximately 1 743 000 m^3 (i.e., 142 854 m^2 $\times$ 12.2 m). Hazardous soil was placed in the landfill cell and compacted without further treatment[9]. Therefore, we assumed that the contaminated soil from the site consumed a maximum of 1.2% of the landfill if not compressed. This disturbance was addressed qualitatively in Section 4.6.23.

Emissions. Two types of emissions are of concern regarding the deposition of contaminated soil in a hazardous landfill: dust and leachate. Again, as for non-hazardous landfill, it was difficult to estimate emissions for the soil considered here. Solid wastes (e.g., contaminated soil) are often deposited by luggers into the base of the cells and dust generation is kept below grade to minimize dispersion by wind [Laidlaw 1994]. Precipitation that comes into contact with the exposed waste face is treated as landfill leachate, pumped to the landfill face, aerated and incinerated along with process water in a liquid waste incinerator. To monitor the integrity of the landfill operation, indicator parameters (e.g., chloride, conductivity, sodium, sulphate) are measured in the groundwater. To date, these parameters have remained fairly constant with time.

We are also concerned about breaches in the landfill at closure or post-closure. For the hazardous landfill under consideration, the estimated closure date is 20 to 50 years. Waste management activities will continue for approximately 20 additional years after closure. These activities include construction of the cap to its final elevation, addition of topsoil, establishment of vegetative cover, monitoring (e.g., surface water, groundwater), and maintenance (e.g., drainage control systems, landfill cap, perimeter berm). After cessation of all waste management activities, the post-closure phase begins (i.e., in 40 to 70 years) and passive systems will control the release of contaminants. It is estimated that the first measurable impact that the landfill will have on the bedrock "contact zone" will occur in over 1000 years, and a single pumping well (operated intermittently) will be sufficient for several centuries. These time frames are beyond our life-cycle time boundary of 25 years. Within the LCA time boundary, it is likely that the landfill site will remain open, and any significant deterioration or maintenance will not occur.

SUMMARY

Table 4-27 Summary for deposition of soil in hazardous landfill

Inputs		*Outputs*	
hazardous soil (including stabilized soil)	50 380 tonnes	soil as solid waste (hazardous)	50 380 tonnes
water treatment sludge	95 tonnes	sludge as solid waste	95 tonnes

4.6.18 Waste Management: Deposition of Contaminated Water in Hazardous Landfill (16)

PROCESS DESCRIPTION

Contaminated water was pretreated prior to landfilling, to render it acceptable for disposal. The pretreatment of industrial wastes included neutralization and solidification. Neutralization involved mixing waste acids and alkali and/or neutralization reagents to produce a neutral non-corrosive aqueous slurry. Solidification involved mixing the slurry with fly ash (90%) and bag house dust from the liquid waste incinerator (10%), or even

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[8] This assumed a density of 2400 kg/m^3 that would be expected from the addition of water for dust control.
[9] Schutte, R. 1996. pers. comm.

some dusty solid wastes, thus generating a solid suitable for disposal. If solidification is not used, the slurry may be dewatered.

INPUTS AND OUTPUTS

Contaminated water sent to a hazardous landfill was 108 tonnes. It was difficult to determine the nature of subsequent treatment of the water, for example, whether it was neutralized along with other waste and then dewatered, or solidified. As a maximum (i.e., assuming that it was not dewatered), the contaminated water contributed 108 tonnes to the landfill. The amount of solidification agent has not been included. The landfill contributes to the land use (e.g., excavation, land fragmentation) outside of the contaminated site itself. This disturbance was qualitatively addressed in Section 4.6.23.

SUMMARY

Table 4-28 Summary for deposition of contaminated water in hazardous landfill

Inputs		*Outputs*	
contaminated water	108 tonnes	water as solid waste (hazardous)	108 tonnes

4.6.19 Transportation: On-Site

Transportation activities are not reflected in Figure 4-1, however transportation between and within modules occurred for many of the activities described above. For example, clean backfill from the borrow pit was transported to the excavation pit at the contaminated site. Distinctions have been made between on- and off-site transportation, and on-site transportation activities were included within modules. Some information on the emission factors for on-site transportation activities was given in Section 4.6.9 and 4.6.10. Off-site (i.e., between module) transportation was addressed in Section 4.6.20.

ON-SITE TRANSPORTATION

The energy-consuming processes occurring on-site were all transportation-related, with diesel fuel as the energy source. These activities combine those associated with site excavation (1) and backfilling (2), as discussed in Sections 4.6.9 and 4.6.10, respectively. Several different vehicle types were used on-site, including a track mounted backhoe, bulldozer, vibratory compactor and loader.

Factors affecting transportation emissions included: the nature of the road surface, the aerodynamic efficiency of the vehicle, topography of the route, type of operation, load, and driving technique [Garret 1994]. These emissions were calculated using emission factors appropriate to the type of vehicle, loading and fuel type. Typical emission factors for trucks using diesel fuel are given in Table 4-29.

Table 4-29 Emission factors for air emissions related to diesel-fueled transportation[1].

Emission	*Emission Factor*	*Application*	*Reference*
CO_2	2730 g/L fuel	• on-site transport	• Jacques (1992). Based on heavy-duty diesel vehicles.
	86.15 g/tonne-km	• off-site transport	• Transport Concepts (1995). For 1990 semi-truck vehicles with partial loads
VOC	0.173 g/MJ	• on-site transport	• Transport Concepts (1995). For 1990 semi-truck vehicles with partial loads, 1.2 MJ/tonne-km conversion.
	0.19 g/tonne-km	• off-site transport	• ORTEE (1992). For 1990 diesel truck with general freight.
CH_4	0.2 g/L fuel	• on-site transport	• Jacques (1992). Based on heavy-duty diesel vehicles.
	0.005 g/MJ	• off-site transport	• Jacques (1992). Calculated from value given.
N_2O	0.4 g/L fuel	• on-site transport	• Jacques (1992) Based on heavy-duty diesel vehicles.
	1.33 g/tonne-km	• off-site transport	• ASG AB (1995). For 1990 long-distance truck with 50% loading.
particulates	0.08 g/MJ	• on-site transport	
	0.095 g/tonne-km	• off-site transport	
CO	2.04 g/MJ	• on-site transport	• Transport Concepts (1995). For 1990 semi-truck vehicles with partial loads, 1.2 MJ/tonne-km conversion
	2.45 g/tonne-km	• off-site transport	• Transport Concepts (1995). For 1990 semi-truck vehicles with partial loads.
SO_2	0.225 g/MJ	• on-site transport	• ORTEE (1992). For 1990 diesel truck with general freight, 1.2 MJ/tonne-km conversion.
	0.27 g/tonne-km	• off-site transport	• ORTEE (1992). For 1990 diesel truck with general freight.

[1] The emission factors chosen were appropriate for 1992 and 1993.

4.6.20 Transportation: Off-Site

PROCESS DESCRIPTION

Off-site transportation involved moving materials between modules, for example, moving excavated contaminated soil to the disposal facility. For the case study, the information recorded included the number and weight or volume of each load leaving the site. The distances from the site to the various receiving areas were determined from road maps of the area. The transportation of small amounts of materials (e.g., water treatment chemicals) was not considered. Understanding vehicle use efficiency is important when calculating the amount of energy consumed and, subsequently, the environmental impact of the transportation system since it is the major activity in this remediation method.

INPUTS AND OUTPUTS

Inputs	*Outputs*
• diesel for transport of asphalt from 4 to 3	• transportation emissions
• diesel for transport of backfill from 5 to 2	• transportation emissions
• diesel for transport of soil from 1 to 14	• transportation emissions
• diesel for transport of soil from 1 and 11 to 15	• transportation emissions
• diesel for transport of fly ash from 6 to 11	• transportation emissions
• diesel for transport of sludge from 13 to 15	• transportation emissions
• diesel for transport of water from 13 to 16	• transportation emissions
• other energy (11% addition for fuel production)	

The vehicles used for off-site transportation were diesel fueled. Energy consumption factors reported in Table 4-30 were used to calculate the amount of transportation energy consumed. These factors are reported for various means of transport and the units are energy per load weight per distance (e.g., units of MJ/tonne-km, or kWh/tonne-km). Different energy consumption or loading factors were also suggested according to the weight of the payload [Deloitte and Touche 1991].

Table 4-30 Energy consumption factors for various transportation modes.

Transportation Mode	*Energy Consumption Factor* (MJ/tonne-km)	*Load Factor* (%)
long distance truck (maximum load 40 tonnes)	0.6 $^{(a)}$ [ASG AB 1996]	70
medium truck (maximum load 20 tonnes)	1.2 $^{(a)}$ [ASG AB 1996]	50
local truck (maximum load 12 tonnes)	1.8 $^{(a)}$ [ASG AB 1996]	50
highway truck (for payloads under 20 tonnes)	1.2 [D&T 1991]	not specified
highway truck (for payloads 20 tonnes and up)	0.9 [D&T 1991]	not specified
truck (for hire, classes I and II)	1.4 $^{(b)}$ [Khan 1991]	not specified

(a) Original units given as kWh/ton km
(b) Original units given as kJ/tonne km

Factors influencing the choice of energy consumption factor included the nature of transportation (e.g., type of vehicle, highway versus city driving where long distance transportation is more fuel efficient than local transportation) [Garret 1994]. As well, the energy consumption factor is lower for greater payloads. Closely related to the energy consumption factor is the "loading factor". The loading factor, similar in concept to "degree of fullness" or "degree of utilization", describes how efficiently the vehicle is used in transport [ASG AB 1996]. Currently, there are no generally accepted methods for measuring transport efficiency. "Load factor" may be defined as the "net payload of a car after deducting empty miles and partial loads" [Garret 1994]. "Degree of fullness" is sometimes stated as a cross-section of a trip, including only the degree of fullness in a truck while going to the recipient and not specifying the lower degree of fullness (e.g., empty) when returning.

The following assumptions were made when choosing an energy consumption factor:

- transportation was mainly on highways
- trucks carried weights of over 25 tonnes when full
- trucks were filled to capacity by volume when travelling to the receiving site, and returned empty (approximately 50% loading factor for return trip).

For this study, the energy consumption factor was chosen as 0.9 MJ/tonne-km with the payload averaged over the return trip.

Data are given in Table 4-31 and sample calculations are presented below. The data quality summary for transportation off-site is **(1,4/1/1/2,3)**.

Sample Calculation

For the transportation of 312 return loads of non-hazardous soil over 140 km (i.e., each way 70 km), where the average mass per load was 19.9 tonnes/return load, the energy requirement is calculated as:

transportation energy requirement

= return trip distance × number of return loads × average weight/return load × energy consumption factor

$$= 140\ \text{km} \times 312\ \text{return loads} \times 19.9\ \frac{\text{tonnes}}{\text{return load}} \times 0.9\ \frac{\text{MJ}}{\text{tonne - km}}$$

= 782 309 MJ.

Table 4-31 Summary of energy requirements for off-site transportation.

Medium Transported	*Return Trip Distance* (km)	*Number of Return Loads* (return loads)	*Average Mass/Return Load* (tonnes/ return load)	*Total Mass Transported* (tonnes)	*Transportation Energy Consumption* (MJ)
Soil					
hazardous	614	1523	16.5	50380	13 920 000
non-hazardous	140	312	19.9	12418	782 300
clean backfill	120	2502	13.4	67539	3 647 000
Other					
contaminated water	210	3	18	108	10 200
asphalt	120	7	18.75	261	14 200
water treatment sludge	614	3	15.8	95	26 200
fly ash	628	8	18.8	300	85 000
				total:	18 485 000
				transportation energy:	16 653 000
				other energy:	1 831 800

Transportation emissions. Emissions were calculated using emission factors as discussed above and presented in Table 4-29. Transportation emissions associated with off-site transportation activities are given in Table 4-32.

Solid waste in the form of mineral waste is also associated with fossil fuel combustion. Overall, 5332 tonnes of mineral waste was produced.

Sample Calculation

CO_2 emissions for clean backfill

= 86.15 g/tonne-km × 120 km × 2502 loads × 13.4 tonnes/load

= 346 341 kg

Table 4-32 Summary of transportation emissions associated with off-site transportation activities.

Off-Site Transportation of:	*Emissions* (kg)							
	CO_2	*VOC*	*CH_4*	*N_2O*	*particulates*	*CO*	*SO_2*	*NO_x*
hazardous soil	1 332 452	2 939	69.6	144	1 469	37 894	4 176	14693
non-hazardous soil	74 887	165	3.9	8.1	83	2 130	234	826
clean backfill	349 109	770	218.2	37.7	382	9 928	1 094	3850
contaminated water	977	2	0.05	0.11	1	28	3	11
fly ash	8 115	18	0.42	0.88	9	230	25.4	90
asphalt	1 350	3	0.07	0.15	1.5	38.4	4.2	15
water treatment sludge	2 512	6	0.13	0.27	2.8	71.5	7.9	28
total:	1 769 403	3 902	92.4	191.1	1 951	50 320	5 545	19 512

Table 4-33 Emissions associated with precombustion energy

Emissions	*Amount* (kg)
CO_2	115 016
CH_4	1 191
NO_x	1 191
CO	32.9
Solid Waste	
mineral waste	904
ash	1027
inert chemicals and industrial waste	197

4.6.21 Transportation: Wastewater Pumping

PROCESS DESCRIPTION

The wastewater (i.e., contaminated groundwater, rainwater) was pumped from where it accumulated in the excavation pit to the water treatment system. This water did not include grey water from showers and laundry usage that was part of the total amount of water discharged from the site. The data quality summary is **(1,5/6/2/3)**.

INPUTS AND OUTPUTS

To calculate the amount of energy required to pump the wastewater, the following assumptions were made:

- maximum height of water pumped was 6 m
- estimated efficiency of pump was 77% [Perry's 1984]
- density of the wastewater was that of water.

Sample Calculation

energy required to pump wastewater to on-site treatment facilities

= volume of wastewater × density of water × gravitational acceleration × height/pump efficiency

$= 11430.03\ \text{m}^3 \times 1000\ \text{kg/m}^3 \times 9.81\ \text{m/s}^2 \times 6\ \text{m}/0.77$

= 873 MJ

To account for the energy lost through use of a generator, an additional energy consumption of 20% (175 MJ) was assumed, bringing the energy consumption to 1049 MJ (and assuming 11% precombustion energy) and total energy use to 1164 MJ.

4.6.22 Monitoring (10, 12)

Major monitoring activities occurred during site excavation and backfilling (especially in light of the desire to mitigate the dispersion of lead-contaminated dust), and are represented in Figure 4-5 by modules (10) and (12). The monitoring methods included deploying dustfall jars, hi-vols (i.e., high volume blower draws air through a filter), mini-rams (i.e., portable, real-time monitoring of dust or fumes), lo-vols (i.e., low volume air samplers), and portable air monitors (i.e., PAMs). The energy use associated with all of the monitoring equipment was assumed to be minimal.

4.6.23 Site Quality Indicators and Other Observations

Site quality indicators are used for the Life-Cycle Impact Assessment. Our interest focused on the concentration of various contaminants left on-site in the soil and groundwater. We assumed that non-chemical indicators would reflect an improvement in

conditions considering the long history of heavy industrial usage. Additional information was the area of soil remediated in relation to the total site area.

SITE QUALITY MEASURES

Soil quality measures, given in Table 4-34, were used to estimate the post-remediation quality of the site. These measures were necessary to capture the quality of the soil, because soil was included in the system boundary. Note that for "concentrations of contaminants on-site", three areas of the site were identified: area 1 (i.e., backfilled area), and areas 2 and 3 (i.e., contaminants remaining on-site in two distinct geographic regions).

Table 4-34 Summary of on-site soil quality measures

Parameter		*Value*
• particle size distribution		granular A and B
• concentrations of contaminants on-site [µg/g]	*area 1*	Pb: <5 – 12 PAH: < 1 As: <0.1 – 0.6 Cd: <0.5 – 1.4
	area 2	Pb: 190 – 760 PAH: 5800 to 6550 As: 1.4 – 7 Cd: 1- 2
	area 3	Pb: 2280 PAH: NA As: 0.8 Cd: 2.1

NA – not available

DISTURBANCE INFORMATION

Potential impacts from disturbances related to all activities undertaken to remediate the site are summarized in Table 4-35 according to stressor category.

Table 4-35 Summary of Disturbance information given by stressor category.

Stressor Category	*Information*
• non-remediation of land	• Portions of the site remain contaminated, contributing to land stagnation. See Section "Area of Remediated Site" below.
• off-site (i.e., outside of contaminated site boundary) construction, excavation, land fragmentation	• Off-site activities occur for modules 6- 8. "Land use" associated with landfills occurs in modules 14-16. This disturbance potentially contributes to habitat alteration or destruction in these regions.
• compaction, paving, application of impervious surface	• A portion of the contaminated site is paved, potentially effecting soil moisture, aquifer recharge, and ecosystem regeneration.
• human social stressors	• During remediation at the site, potential human social disturbances stem from construction and transportation noise, dust generation, and diminished aesthetic value. Similar stressors are associated with "off-site" modules 14-16 and 5.

AREA OF REMEDIATED SITE

Total area of site is 14 975 m^2. The area of paved cover was 2500 m^2, or 17% of total site area. In addition to the paved area, an additional 1627 m^2 or 11% of total site area contained contaminated soil at depth. The total area of the site that either had contaminated soil at depth and/or was paved was 4127 m^2 or 28% of the site.

4.7 SUMMARY OF INVENTORY RESULTS AND DISCUSSION

The *Inventory* data for the site remediation and related activities are summarized in Table 4-36. The *Inventory* items, listed as stressors, are subdivided by impact category (i.e., *Pollution, Disturbance* and *Depletion*) and also by stressor category for four life-cycle stages: raw materials and energy acquisition; site processing; waste management; and transportation. Note that "transportation" involves only the activities facilitating movement between modules, as represented by the broken lines joining selected modules in Figure 4-1 (e.g., trucking clean backfill from "clean backfill production" to "backfilling"). Distribution, or "on-site" transportation activities, is incorporated within each module. For example, site excavation involved the operation of backhoes, loaders and bulldozers, and associated inputs and emissions are grouped under "site processing". In addition, the inventory items associated with energy acquisition have been grouped under "fossil fuel use and energy consumption" and are, therefore, allocated to their respective life-cycle stage (e.g., precombustion emissions and energy associated with backfill production are grouped under the raw materials acquisition life-cycle stage).

The *Inventory* presented Table 4-36 is in the format of the Potential Impacts Checklist, which links stressors and potential impacts according to stressor and impact categories. Items in each category are discussed below.

POLLUTION

These stressors are grouped under three main stressor categories: (i) acid emissions; photochemical smog precursors, and greenhouse gases; (ii) contaminants and particulates emitted to air; and (iii) contaminants discharged to water.

Emissions of acidic species, air pollution, photochemical smog precursors, and greenhouse gases are largely related to fuel combustion for site processing, raw materials acquisition, and transportation life-cycle stages. These emissions were calculated from energy consumption values (see fossil fuel use under Depletion) using emission factors from several sources, appropriate for the 1992-1993 time frame [Jacques 1992, ORTEE 1992, Transport Concepts 1995, NEB 1994, ASG AB 1996, Khan 1991, Covery 1976]. Overall, the majority (72–78% for each stressor) of emissions were associated with off-site (i.e., between-module) transportation activities. Within these transportation activities, the major contributors to Pollution were from the transportation of hazardous soil to the hazardous landfill site (75% of the transportation life-cycle stage's CO_2 emissions) and transportation of clean backfill (20% CO_2). Transportation of non-hazardous waste, water treatment sludge, and other materials resulted in negligible contributions to total emissions.

Within the raw materials acquisition life-cycle stage, the majority of the emissions were related to clean backfill production (e.g., CO_2 82% of total; NO_x and C_xH_y 97%; CO and particulates 100%). Asphalt production, however, contributed 42% of methane emissions while hydrated lime production contributed negligibly. Potential emissions from asphalt-laying (e.g., benzene, PAHs, lead, total and PM10 particulate, CO, SO_2 [Ullman's 1985, U.S. EPA 1994]) have not been assessed. For site processing activities, the majority (>96%) of these Pollution emissions were related to site excavation activities.

Table 4-36 Summary of life-cycle inventory data by life-cycle stage

Stressor Category	*Stressor*	LIFE-CYCLE STAGES *Raw Materials Acquisition*	 *Site Processing*	 *Waste Management*	 *Transportation*
Pollution					
Acid Emissions / Photochemical Smog Precursors	• NO$_x$ (kg)	3 120	2 950	-	20 700
	• SO$_2$ (kg)	800	776	-	5 545
	• particulates (kg)	285	276	-	1 951
	• VOC (kg)	615	597	-	3902
Greenhouse Gases	• CO$_2$ (kg)	334 000	265 000	-	1 884 000
	• C$_x$H$_y$ (kg)	270	240	-	1 284
	• CO (kg)	7 260	7 040	-	50 400
	• NO$_x$ (kg)*	3 120	2 950	-	20 700
Contaminants / Particulates to Air	• coarse dust (kg)	-	1 400	-	-
	• lead (kg)	-	3 57	-	-
Contaminants in Surface and Groundwater	• fluorine (kg)	-	-	4 51	-
	• silver (kg)	-	-	0.05	-
	• aluminum (kg)	-	-	116	-
	• arsenic (kg)	-	-	5.81	-
	• cadmium (kg)	-	-	1.60	-
	• chromium (kg)	-	-	0.40	-
	• copper (kg)	-	-	13.5	-
	• iron (kg)	-	-	550	-
	• lead (kg)	-	-	91 1	-
	• phosphorus (kg)	-	-	6.11	-
	• zinc (kg)	-	-	13.0	-
	• BOD (kg)	-	-	60.0	-
	• TSS (kg)	-	-	4530	-
Disturbance					
Non-Remediated Land	• contaminated land (m^2)	-	4127	-	-
Application of impervious surface	• capped land (m^2)	-	2 500	-	-
Aquifer quality stressors	• groundwater (kg)	-	-	8 000 000	-
Depletion					
Fossil Fuel Use / Energy Consumption	• diesel (GJ)	3560	3450	-	16 700
	• oil (GJ)	85.4	-	-	-
	• natural gas (GJ)	11.5	-	-	-
	• coal (GJ)	0.814	-	-	-
	• nuclear (GJ)	1.64	-	-	-
	• hydro (GJ)	0.357	-	-	-
	• precombustion (GJ)	401	380	-	1 831
	• other fuel (GJ)	-	1.05	-	-
	• coal (raw material) (kg)	300 000	-	-	-
	• crude oil (raw material) (kg)	26 100	-	-	-
Solid Waste	• non-hazardous soil (kg)	-	-	12 400 000	-
	• hazardous soil (kg)	-	-	50 380 000	-
	• hazardous sludge (kg)	-	-	95 000	-
	• hazardous water (kg)	-	-	108 000	-
	• mineral waste (kg)	215	169	-	6 244
	• ash (kg)	207	192	-	1 030
	• inert chemicals / industrial waste (kg)	42.9	36 8	-	197
	• drillings / cuttings (kg)	36.3	-	-	-
Water Use	• water (kg)	195	-	3 430 000	-
Mineral / Soil Use	• aggregate (kg)	235 000	-	-	-
	• clean soil (kg)	67 500 000	-	-	-
	• limestone (kg)	1 080	-	-	-

* Listed again for illustrative purposes.

Excavation and backfilling activities contributed to emissions of particulates to air (i.e., coarse dust and lead associated with airborne particles). These emissions were measured as dustfall and total lead in dustfall, and reported on a monthly basis over the duration of the remediation activities, including the shut-down period.

The concentrations of several contaminants were determined in discharged wastewater (e.g., BOD, TSS, aluminum, arsenic, iron, and lead). Analyses were carried out on each batch of wastewater discharged, and the concentrations were correlated to the appropriate wastewater volume discharged to calculate the total mass of the waterborne emissions. Water from several sources was collected and treated together: water for dust mitigation (e.g., wetting excavation site, washing trucks); grey water (e.g., showers and laundry); rainfall; and groundwater. As mentioned in the boundary description, only activities associated with the excavation and disposal of contaminated soil and groundwater were included. However, it was not possible to distinguish between water sources, consequently water generated by activities such as the power-washing of building surfaces should not have been, but were by necessity, included in the analysis. Therefore, it should be noted that the total amount of contaminants discharged in the water was potentially greater than that associated only with excavation and disposal activities.

DISTURBANCE

Disturbance refers to on- and off-site disruption, degradation or restriction of land, and groundwater quality. Off-site land quantity (e.g., related to waste disposal), and water and backfill use are discussed under "Depletion". The Disturbance stressor categories may be grouped into: (i) disturbances to land through non-remediation of land or application of an impervious surface; and (ii) aquifer stressors. At the contaminated site, regions remained contaminated and a portion of the site was capped. Overall, 28% of the site area had contaminants at depth and/or was paved. The major stressor to the aquifer was associated with the removal of approximately 8000 m^3 of groundwater, and capping, which restricts recharge.

DEPLETION

Over 70% of all fossil fuel and energy consumption was associated with the transportation life-cycle stage. Of this, transporting hazardous soil consumed the greatest proportion of energy (75% of Transportation energy). Clearly, this impact is sensitive to the distances involved, e.g., contaminated site to three sites (hazardous and non-hazardous disposal and clean backfill). For off-site transportation (i.e., between modules), fossil fuel use was estimated using information from transportation logs (e.g., payload, vehicle type, haulage route), energy consumption factors [ORTEE 1992, Transport Concepts 1995, ASG AB 1996, Khan 1991, Garret 1994] and mode of travel considered.

Most of the "fossil fuel use and energy consumption" for Raw Materials Acquisition and Site Processing was associated with distribution (i.e., on-site transportation). For "site excavation" and "backfilling", the remediation contractors estimated fuel consumption for each vehicle-type over the duration of the remediation project (e.g., volume of diesel consumed per vehicle per day). The related energy consumption, including precombustion energy, was then calculated from these estimates [ORTEE 1992, NEB 1994, Covery 1976]. Energy consumption was calculated similarly for "clean backfill production".

Throughout the project, diesel fuel was the main energy type used, along with natural gas and electricity, with electricity from the Ontario grid (comprised of 45% nuclear, 32% hydro, 23% coal). "Hydrated lime production" used energy to mine the limestone, and raise it to decomposition temperature [Encyclopedia of Chemical Processing and Design 1988, Kirk-Othmer 1978, Goldfarb et al. 1984, Young 1996b], using natural gas, transportation fuels, and electricity. "Asphalt production" required energy to produce asphalt, mine mineral aggregates, and prepare asphalt-aggregate mixes [Ullman's 1985, Handbook of Petroleum Refining Processes 1996]. The energy associated with the production of fly ash, as discussed below, was not included in the analysis.

Fly ash and asphalt are by-products of coal combustion [Perry's 1984] and crude soil refining [Handbook of Petroleum Refining Processes 1996, Kirk-Othmer 1992], respectively. For the case study, the fly ash originated from a local utility, where approximately 0.073 tonnes of ash is produced per tonne of coal. Since the purpose of

coal combustion is predominantly energy production, fly ash may be considered as a waste or co-product. The total amount of coal used to produce fly ash was allocated on a mass basis [Henshaw 1994], and appears in Table 4-36 as "coal (raw material)" with no assigned environmental burdens (i.e., zero-allocation). Asphalt is one of many petroleum products produced from crude oil [Handbook of Petroleum Refining Processes 1996]; again, allocation of crude oil and the fraction of energy use allotted to asphalt production was made on a mass basis [Henshaw 1994].

Solid waste was produced from site excavation, where 82% of the excavated soil was considered hazardous and deposited in hazardous landfill. In addition, hazardous wastewater and water treatment sludge were removed from the site and landfilled. Other solid wastes produced (e.g., mineral waste, ash, inert chemicals, drillings, cuttings) were associated with the precombustion of fossil fuels [Jacques 1992, NEB 1994, Young 1996b].

As mentioned, process water was used for many activities, including dust mitigation. The total amount of process water used was estimated as 3430 m^3. In addition, water was used in the production of hydrated lime [Encyclopedia of Chemical Processing and Design 1988], although this amount was negligible in comparison to the total amount of process water used on-site.

Included under Mineral and Soil Use were the aggregate used for the asphalt cap [Ullman's 1985], and limestone used in the production of hydrated lime [Encyclopedia of Chemical Processing and Design 1988]. Clean soil taken from a borrow pit to backfill the excavated site was also included here, the amount being calculated from logs of the mass and number of individual loads brought on-site.

4.8 LCA: IMPACT ASSESSMENT

Life-Cycle Impact Assessment (LCIA) was used to evaluate the potential impacts of stressors on ecosystems, human health and natural resources. Quantitative potential impact indicators were used as surrogates of these impacts and, for this study, the streamlined Impact Assessment included: (i) process-related impacts; and (ii) site-related impacts. The impacts determined quantitatively were few in comparison to the comprehensive coverage presented in the qualitative "Potential Impact Checklist". Few quantitative stress-impact models have been developed, which restricted our ability to conduct a full Impact Assessment. In this study, we have contributed the LCIA by further developing two toxicity indicators.

Process-related potential impacts were derived from the Inventory and relate to the activities presented in Figure 4-1. The process-related impact indicators applied in this case study include: Global Warming Potential (GWP), Gross Energy Requirement (GER), Solid Waste Burden (SWB), and process-related ecological and human toxicity potential impacts. The sensitivities of GWP, GER, and SWB to the varied input parameters, as mentioned for the Inventory, are presented. Young [1996b] used these indicators in his life-cycle assessment of raw materials and selected products.

By contrast, site-related potential impacts refer to the status of the site itself and are associated with soil and groundwater contaminants remaining on-site. The two approaches for assessing these potential impacts include: (a) a land-use measure; and (b) an analysis of the portion of the site containing contaminant levels that exceed ecotoxicity-based soil remediation criteria.

4.8.1 Process-Related Impacts

GWP, SWB AND GER IMPACT INDICATORS

GWP is an index reflecting the contribution of various greenhouse gas emissions to atmospheric global warming, weighted relative to carbon dioxide. For this study, radiative forcing values were derived from the Intergovernmental Panel on Climate Change (IPCC) [1995], assuming a time horizon of 100 years and expressed as a CO_2-equivalent mass. The total GWP for the case study was 3.77×10^6 kg CO_2-equivalent (i.e., on a per site basis).

SWB is a cumulative measure of solid wastes emitted from the life-cycle stages and is given in mass units. Although SWB does not relate directly to an impact and does not capture the number of sites affected, it is indicative of land consumption for disposal, total material use, and the potential for chemical emissions from disposal sites. Two methods for calculating SWB have been used: SWB_A includes all solid wastes generated

from all life-cycle stages; and SWB_B excludes all soils (e.g., hazardous and non-hazardous soil) and sludges coming from the site, and includes only mineral waste, ash, inert chemicals, industrial waste, and drillings and cuttings. SWB_A was approximately 63 000 tonnes, whereas SWB_B was only 7.46 tonnes.

GER is a measure of the total quantity of energy used in processes or activities included within the system boundary, including both combustion and precombustion energy requirements. Similarly to SWB, GER, expressed as GJ, does not measure an impact directly, but relates to fuel consumption, air emissions and land disturbance associated with the many facets of energy production and use. GER was estimated as 2.64×10^7 GJ, on a per site basis.

Figure 4-2 illustrates the relative contributions of the life-cycle stages to GWP, GER, and SWB_A and SWB_B. The major contribution to GWP and GER comes from Transportation (76% and 70% respectively). Young [1996b] noted the strong correlation between these two impact indicators, as occurs in this study. SWB_A, which includes all solid wastes, was dominated by the Waste Management life-cycle stage; however SWB_B, where soils and sludges were excluded, revealed that the majority (88%) of these solid wastes were related to Transportation activities.

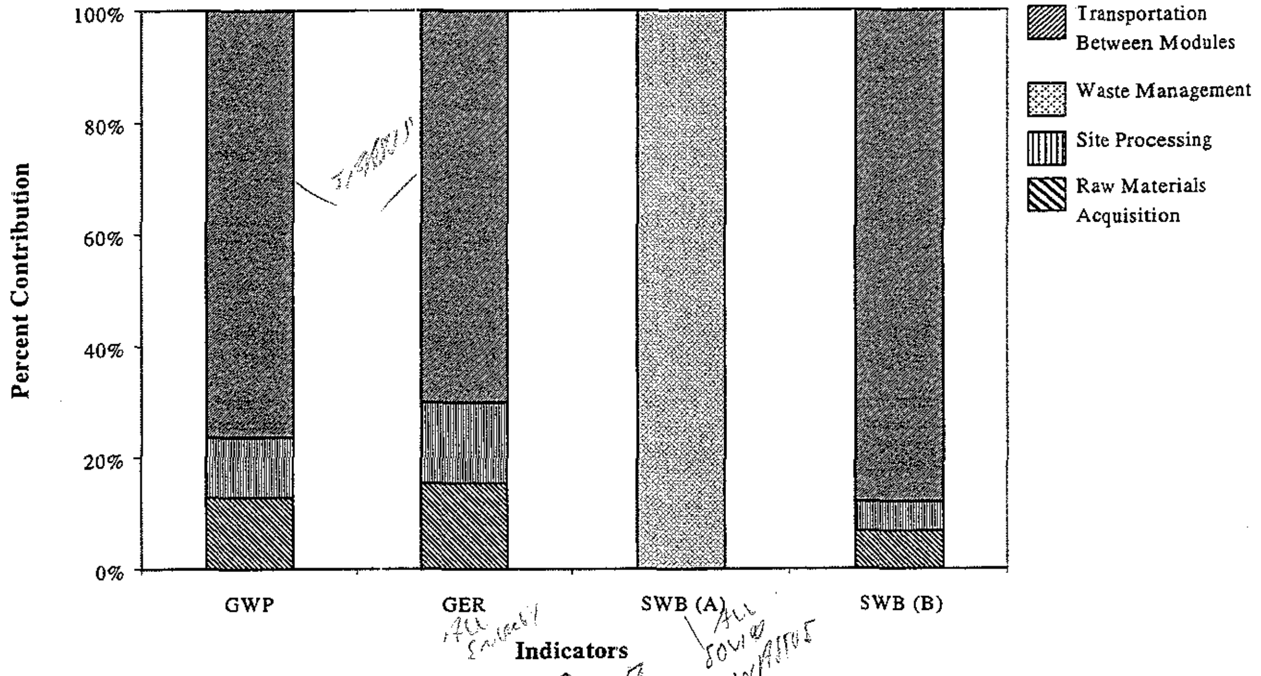

FIG 2 ?

Figure 4-2 Distribution of indicators among life-cycle stages

TOXICITY IMPACTS

LCAs are generic by nature, often lacking a specific geographic (i.e., spatial) and temporal context. The analysis is usually presented according to functional units and thus represents an assessment of incremental, rather than cumulative environmental burden which is indicative of actual impacts. Consequently, LCIA cannot easily draw exposure information from the Inventory data for toxicological evaluations. LCIA, therefore, is not equivalent to risk assessment, which attempts to quantitatively estimate human and/or ecosystem risk. Assessing potential human and ecosystem impacts through LCIA, even at a general level, requires numerous assumptions in order to estimate relative exposure and hence the toxicity potential of inventory items.

Many approaches exist for assessing human and environmental health impacts, including critical volume, direct valuation, health reference, and generic exposure [SETAC 1993a, ILSI 1996, Guinée and Heijungs 1993]. For this study, a generic exposure approach was used for assessing human toxicity and ecotoxicity. The approach involved translating an Inventory emission to an exposure or dose to a human or ecosystem receptor using a Mackay Level III multimedia environmental model [Jia et al. 1996, Mackay et al. 1992, Mackay and Diamond 1989, Diamond et al. 1993]. As discussed by Guinée and Heijungs [1993], the effect component must be based on human toxicological measures such as NEI (i.e., no-effect intake) for oral and respiratory effects. Regulatory toxicity values such as RfD or ADI should be avoided because they do not necessarily indicate a chemical's toxicity alone [ILSI 1996]. NEC (i.e., no adverse effect concentration) should be used for terrestrial and aquatic ecosystem toxicity. For each chemical emission, the exposure and effect are combined to yield a ratio indicative of the risk of toxicity, as elaborated below.

In this study, the generic exposure approach was modified to account for three considerations. First, the chemicals of concern were metals emitted to air and water compartments. Since metals (with the exception of mercury) are not volatile, the use of fugacity as an equilibrium criterion was not appropriate and the equilibrium criterion "aquivalence" was used instead [Mackay and Diamond 1989, Diamond et al. 1993].

Second, a discrete period of emission was determined (i.e. inventory items were emitted over a 75 week period) hence an emission rate rather than an amount was determined. Third, the geographic area of concern was southern Ontario and the "unit world model" was therefore tailored to the southern Ontario area [Mackay and Paterson 1991]. Table 4-37 contains the subcompartment volume fractions for each major compartment and Table 4-38 contains the parameters for major compartments for southern Ontario [Mackay and Paterson 1991].

Table 4-37 Subcompartment volume fractions for main compartments of southern Ontario model

Major compartments	*Density* (kg/m^3)	*Volume fractions for subcompartments*				*Fraction in solids compartments*
		air	water	solids	biota	organic carbon
air	1.19	1.0	0	2×10^{-11}	0	N/A
water	1000	0	1.0	5×10^{-6}	1×10^{-6}	0.2
soil	1500	0.2	0.3	0.5	0	0.02
sediment	1420	0	0.7	0.3	0	0.04

Table 4-38 Major compartments for southern Ontario model

Major compartments	*Density* (kg/m^3)	*Volume* (m^3)	*Areas* (m^2)	*Depth* (m)
air	1.19	4×10^{14}	20×10^{10}	2000
water	1000	4×10^{12}	8×10^{10}	50
soil	1500	1.2×10^{10}	12×10^{10}	0.1
sediment	1420	8×10^{8}	8×10^{10}	0.01

The fate of selected metals emitted to water was calculated using the Level III model for metals. The partition coefficients used are given in Table 4-39 and the input flux and output concentrations are given in Table 4-40. As expected, metals introduced to water tend to accumulate in sediment.

Table 4-39 Partition coefficients for selected metals

[Ling et al. 1993, Diamond et al. 1994]

	Air-Water (dim)	*Particles-Water* (L/kg)	*Fish-Water* (L/kg)	*Soil-Water* (L/kg)	*Sediment-Water* (L/kg)
arsenic	1×10^{-15}	5×10^{4}	7.36×10^{1}	1.7×10^{4}	1×10^{4}
cadmium	1.33×10^{-13}	3.3×10^{5}	9.26×10^{3}	7.8×10^{2}	2×10^{4}
copper	8.75×10^{-14}	2×10^{4}	2.86×10^{3}	6.67×10^{2}	1×10^{4}
lead	2.85×10^{-13}	6.68×10^{5}	7.69×10^{3}	6.67×10^{4}	3.33×10^{5}
zinc	9.01×10^{-14}	1×10^{6}	8.38×10^{2}	1.0×10^{3}	5.2×10^{4}

Table 4-40 Summary of inputs and results of Mackay Level III model and toxicity analysis

	Arsenic	*Cadmium*	*Copper*	*Lead*	*Zinc*
Emission rate to water (kg/week)	0.077	0.021	0.180	1.215	0.173
Concentrations and Percent Distribution					
water (g/m^3)	1.40×10^{-9}	1.82×10^{-10}	6.54×10^{-9}	8.70×10^{-9}	1.24×10^{-9}
(%)	16	8	26.7	7	6.8
sediment (g/m^3)	3.80×10^{-5}	1.00×10^{-5}	8.90×10^{-5}	5.90×10^{-4}	8.40×10^{-5}
(%)	84	92	73.3	93	93.2
No-Effect Concentrations[1]					
human (g/m^3)	1.4×10^{-2}	2.3×10^{-2}	2.3×10^{0}	3.5×10^{-2}	1.4×10^{1}
aquatic (g/m^3)	4.8×10^{-2}	1.1×10^{-3}	2.3×10^{-3}	3.2×10^{-3}	1.1×10^{-2}
sediment (g/m^3)	8.5×10^{0}	8.5×10^{-1}	2.3×10^{1}	4.4×10^{1}	1.7×10^{2}
Toxicity Ratios					
human	1.0×10^{-7}	7.8×10^{-9}	2.8×10^{-9}	2.5×10^{-7}	8.9×10^{-11}
aquatic	2.9×10^{-8}	1.6×10^{-7}	2.8×10^{-6}	2.7×10^{-6}	1.1×10^{-8}
sediment	4.5×10^{-6}	1.2×10^{-6}	1.0×10^{-5}	6.9×10^{-5}	9.9×10^{-6}

[1] MOEE 1996b, HEAST 1992, IRIS 1993.

For human health, the water concentrations are of concern since water is the main route of exposure. Estimated water concentrations were compared to a "no-effect intake" (NEI), in this case a subchronic oral reference dose [Livett 1988, Ontario Ministry of Environment and Energy 1996b, HEAST 1992, IRIS 1993, Agency for Toxic Substance and Disease Registry 1992] by converting the latter to a concentration assuming a 70 kg body weight and daily water intake rate of 1.5 L/day [Health Canada 1995]. For ecosystem effects, estimated water and sediment concentrations were compared to "no adverse effect concentrations" (NEC) derived from the lowest observable effects levels (NOEC) which, in this case, was the final chronic criterion based on the 5th percentile of the screening level concentration [Ontario Ministry of Environment and Energy 1996b].

Equation 1
$$TR_{i,j,k} = \frac{C_j}{NEI_{i,j,k} / 70\,\text{kg} \times 1.5\,\text{L/day}} \ or \ \frac{C_j}{NEC_{i,j,k}}$$

where	*TR*	Toxicity Ratio
	i	receptor system considered (human, terrestrial, aquatic, sediment)
	j	contaminant (e.g., As, Cd, Cu, Pb, Zn)
	k	bulk compartment (e.g., water, sediment)
	C	model-predicted concentration
	NEI	no-effect intake
	NEC	no-effect concentration

To account for differences between biological species used in toxicity testing versus relevant species in the ecosystem, extrapolation factors were used to compensate for lack of variability in test species and number of studies [U.S. EPA 1984]. Secondly, complete bioavailability of metals in water and sediment were assumed, which provided a conservative estimate [Campbell and Tessier 1996]. We have not considered metal speciation and metal-metal interactions [Newman and McIntosh 1991, Tessier and Turner 1995] that have not been incorporated into multimedia models.

The results indicate that, for human toxicity and ecotoxicity, lead is of greatest concern. Lead has the greatest emission and then partitions strongly into sediment. In addition, lead has a low no-effect concentration for human and aquatic systems.

For a more complete analysis, effects due to lead emissions to air should be calculated, however that analysis must account for the pulsed emissions that were deposited to land and water. A Level III model assuming a subchronic inhalation effect would be appropriate here. Finally, one might also consider indirect exposure of metals bioaccumulated in food stuffs [Newman and McIntosh 1991].

4.8.2 Site-Related Impacts

LAND USE ASSESSMENT

For the case study, the movement of soil was integral to the treatment option: contaminated soil was excavated and removed from the site, and clean soil was excavated from a borrow pit to fill the excavation. The main purpose of remediating the site was to render the site area acceptable for future use at the detriment of land consumed for the borrow pit and landfill (hazardous and non-hazardous) sites. In order to consider the land use and consumption associated with the entire project over its life cycle, the land area at the site, borrow pit and landfill sites should be compared.

At the contaminated site, approximately 10 850 m^2 of land was remediated to acceptable residential contaminant levels. Approximately 4130 m^2 of the site area was restricted through application of an impervious surface or the presence of high contaminant levels. The total area required to accommodate all solid waste was 2150 m^2 at the hazardous and non-hazardous landfill sites, assuming an average depth of 12.2 m [Laidlaw Environmental Services 1995]. For the borrow pit, the total area required to produce the minerals used in the remediation was approximately 560 m^2 assuming an average depth of 50 m.

Overall, the total area of remediated land was greater than the total amount of area consumed elsewhere. This difference is due to the shallow depth of the contaminated site in comparison to that of the landfill and borrow pit. The use of different depths to calculate areas raises allocation issues concerning the landfill and borrow pit. The depths assumed that the borrow pit and landfill site were established facilities and, therefore, the maximum depths could be accessed. However, if the borrow pit were accessed at its initial phases of use, the depth-to-area ratio would be very low. Finally, simply summing the total "positive" remediated land area with the total "negative" land consumption is suspect. Although the areas are known, their relative value in economic, land use and ecological (e.g., habitat) terms remains unaccounted for.

RESIDUAL HUMAN TOXICITY BURDEN

The Residual Toxicity Burden (RTB) accounts for contaminants remaining in the soil and is intended to capture the potential toxicity to humans associated with these

contaminants should they resurface (e.g., impacts from future disturbance of the site). It also accounts for the theoretical difference between a site with contaminants remaining at depth and a completely clean site.

The RTB, (Equation 2), is dimensionless and similar to a Toxicity Ratio. It is calculated using toxicological data such as Reference Dose (RfD) or Risk Specific Dose (RsD), depending on the contaminant, and converted to a concentration using body mass and standard values for daily intake of soil [Health Canada 1995].

Equation 2 $$RTB_i = \frac{C_i - C_{background,\,i}}{C_{REF\ i}}$$

Where	C_i	mean concentration of contaminant *i* in soil
	$C_{background\,i}$	typical background soil concentration of contaminant *i*
	$C_{REF,i}$	toxicity based reference concentration of contaminant *i* derived from RsD or RfD values.

Values of RTB greater than one indicate future adverse health risk with the possible re-emergence of contaminants. The greater the value, the greater the concern. Negative values indicate background concentrations higher than C_{REF}. The RTB results for the case study are given in Table 4-41 for three areas that differed in residual contaminant concentrations. The results indicate that areas 2 and 3 pose concern for potential human health effects. Soil in these areas would require further remediation should human exposure become likely through future land use (e.g., excavation). Arsenic and cadmium concentrations at the site should theoretically not cause concern should they resurface given negative values of RTB or values less than one.

Table 4-41 Residual Toxicity Burden calculation data and results

	Arsenic	*Cadmium*	*Lead*
Residual contaminant concentration in soil [µg/g]			
area 1	0.35	0.95	8.5
area 2	4.2	1.5	475
area 3	0.8	2.1	2280
Typical background concentration in Ontario soil [µg/g][1]	17	1	120
Toxicity based reference concentration [µg/g]	1.05	1.75	2.625
Residual Toxicity Burden			
area 1	-16	-0.03	-42
area 2	-12	0.29	135
area 3	-15	0.63	823

[1] MOEE 1996b

A similar analysis could be undertaken for terrestrial ecosystem receptors, however, suitable no-effect concentrations appropriate for a variety of organisms must be determined.

4.9 DISCUSSION

CASE STUDY

The investigation of the excavation and disposal case study, through the quantitative detailing of remediation and related activities, has highlighted impacts usually hidden from traditional analyses conducted for contaminated sites such as risk assessment, with its sole focus on potential toxicity impacts. In addition to toxicity, the LCA emphasized the relative importance of energy consumption, solid waste production and land use impacts resulting from clean-up activities. For example, energy consumption, with resultant resource depletion and air pollution impacts, was due to, primarily, off-site transportation. The magnitude of these impacts was a function of the mass of material hauled and distance, where three sites required consideration (hazardous and non-hazardous disposal facilities, and the borrow pit). In addition to transportation-related impacts, solid waste was a concern because of resulting land use impacts at two sites. Thus, the Life-Cycle Analysis of these activities has emphasized the cycle of related land use disturbances from the excavation of a backfill region (i.e., borrow pit), to the transfer of clean fill to the excavation site, whose soil was, in turn, deposited elsewhere. Despite these off-site disturbances, the use of the contaminated site itself remains restricted due to pockets of contaminated soil at depth and, consequently, complete land use has not been restored at the remediated site. Because the life-cycle approach does not discount the value of various lands (e.g., particular communities, land with high or low rent potential, land with distinct aesthetic value), this assessment clearly demonstrates the disruption of three distinct areas.

In traditional applications of LCA, a final check of the *Inventory* data consists of determining whether the overall system balances (i.e., inputs equal outputs). For contaminated sites, however, the processes considered are not continuous and balancing the *Inventory* is not a criterion for the system boundary. Consequently, the difference between inputs and outputs provides useful information about the system. In this case, the *Inventory* revealed net removal of groundwater from the site, reflecting local depletion of the aquifer. A second example is that more clean materials were used to remediate the site than waste removed, indicating a net depletion of land and mineral resources.

Whereas every attempt was made at constructing a complete analysis, several omissions in the *Inventory* and *Impact* Assessment may limit the final conclusions drawn from this analysis. For example, many of the environmental effects resulting from the remediation method have long term effects that were not fully captured by the analysis. Whereas hazardous waste containment may require limited resources and have few effects in the short term, these effects, and resources required to minimize the effects, occur over the long term. Similarly, disturbance at the backfill site and contaminants remaining at the remediated site will result in long term impacts. No plans were in effect for restoring the asphalt cap in future, although this will undoubtedly be necessary in order to minimize potential toxicity impacts. Other *Inventory* omissions have been noted above, and rationalized by an analysis of mass contribution (e.g., emissions related to laying asphalt, inputs and outputs associated with monitoring site excavation and backfilling). Estimating all omitted inventory items, including a non-linear extrapolation over the 25-year time boundary, was beyond the scope of this project, and remains an area for further work. At a minimum, this exercise has resulted in the qualitative assessment of these activities, which is an improvement over assessment methods that do not evaluate impacts throughout the life cycle of an activity.

As with most LCAs, the interpretation of the *Inventory* through the *Impact Assessment* was constrained by the limited number of stressor-impact models [Young 1996b, SETAC 1997]. For example, further work is required to develop an indicator(s) related to land use that imparts information on habitat alteration, the viability of land to support various functions, and land stagnation [Diamond et al. 1998]. We have addressed, but not adequately captured, these impacts through the Land Use and Solid Waste Burden metrics. As a contribution to the *Impact Assessment*, the categories of process- and site-related stressor impacts were developed to clarify the nature and source of impacts, along with toxicity measures suitable for each category.

LCA METHOD

This study has revealed several challenges in using a LCA-based approach for contaminated sites. In the *Initiation* or scoping phase, determining particular activities and processes to be included within the system boundary required considerable judgment, however the goal of the study and definitions of life-cycle stages proved useful for guiding decisions (e.g., inclusion or exclusion of decommissioning activities that were numerous and often inter-related with the soil remediation activities). The definition of the system boundary is an essential step that is necessary before the Inventory component is attempted, yet it requires an in-depth understanding of all related remediation activities that often comes through conducting the *Inventory* analysis. The time horizon of 25 years was intended to capture longer term effects, however these effects proved difficult to estimate and were either not included, or inadequately included within this study (e.g., emissions from the hazardous waste landfill).

The life-cycle stages developed by Diamond et al. [1998] for contaminated site remediation activities were adequate for describing the case study. "Post-site processing" and "monitoring" were not developed due to their minor role in this study. Whereas monitoring played a minor role in the *Inventory*, it provided essential information (e.g., concentrations of contaminants in air, dustfall measures) from which *Inventory* data were derived.

Site-specific remediation data, as mentioned, were taken largely from consultants' reports. Although the entire *Inventory* and subsequent interpretation were reviewed by

remediation consultants and a panel of experts, the process of summarizing data for the public forum, such as this paper, obscures the transparency of the data, which is an unfortunate, yet typical, feature of LCA studies relying on proprietary data. For example, certain reagents were proprietary and thus it was not possible to determine constituents, let alone inputs and outputs for production. This lack of information, while noted, contributed to gaps in the overall Inventory which again, is typical of many LCA case studies. The presentation of *Inventory* data according to a checklist format proved useful for linking inventory items to stressors and, conceptually, to their potential impacts and clarifies the distribution of the Inventory items, relative to life-cycle stage.

The *Impact Assessment* was restricted to a limited number of potential impact indicators that have been developed: GWP; SWB; multimedia contaminant fate and toxicity; land use assessment; and Residual Toxicity Burden. These impact indicators, though few, provide essential information to help interpret the *Inventory*. Here, we have contributed to developing multimedia contaminant fate and toxicity estimates for metals, and have distinguished these effects from those due to contaminants remaining on-site, for which the Residual Toxicity Burden is introduced. The multimedia assessment accounts for the environmental fate of persistent contaminants and represents a more realistic evaluation of contaminant impacts than a non-fate indicator model such as Critical Volumes. Residual Toxicity Burden accounts for contaminants remaining on-site, and reflects their potential toxicity should they resurface.

In summary, we have presented an application of a LCA-based method to site remediation activities that has highlighted important aspects associated with the remedial option. The two components of the LCF, the LCM and LCA have produced qualitative and quantitative assessments, respectively, upon which decisions and choices can be made and opportunities for improvement can be identified. The relative contributions of the life-cycle stages to the overall impacts of the entire remediation approach have been clarified. The case study illustrates the utility and feasibility of taking a life-cycle approach to analyze a process such as site remediation.

Overall, the case study results indicated that remediation of localized contaminated soil results in burdens on local (e.g., contaminants remaining on-site, aquifer depletion), regional (e.g., land or space consumption, mineral consumption, air pollution, potential ecotoxicity, human health impacts), and global scales (e.g., acid rain, global warming, ozone depletion, energy source depletion). Thus, the effects of the excavation and disposal remediation option extend beyond the contaminated site itself, and only become evident when analyzed from a life-cycle perspective.

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6. Appendix

Raw Materials

Summary of Raw Input Data

clean backfill soil	67539 tonnes
asphalt cover	261.25 tonnes
fly ash	300 tonnes
hydrated lime	800 kg
PAC	

Summary of Raw Output Data

discharged water	11431 m3
non-hazardous soil	12418 tonnes
hazardous soil	50380 tonnes
water treatment sludge	95 tonnes
contaminated water	108 tonnes

RAW MATERIAL REQUIREMENTS

Module 4: Asphalt cover production

Asphalt cover

thickness	50	mm				
area	2500	m2	mass of asphalt =	261.25	tonnes	
density	2090	kg/m3				
binder content (wt)	0.1		mass of binder =	26.125	tonnes	= crude oil
aggregate content (wt)	0.9		mass of aggregate =	235.125	tonnes	

Module 9: Dust Mitigation

Process water

water discharged	11431	m3			
fraction of groundwater	0.7		volume of process water =	3429.3	m3
fraction of process water	0.3		volume of groundwater =	8001.7	m3

Module 8: Hydrated Lime Production

$$\underset{\text{limestone}}{CaCO_3} \longrightarrow \underset{\text{lime}}{CaO} + CO_2$$

$$\underset{\text{lime}}{CaO} + H_2O \longrightarrow \underset{\substack{\text{hydrated lime}\\ \text{800 kg}}}{Ca(OH)_2}$$

hydrated lime required	800	kg	
MW of hydrated lime	74	g/mol	
MW of lime	56	g/mol	
MW of limestone	100	g/mol	
MW of carbon dioxide	44	g/mol	
MW of water	18	g/mol	
mol of hydrated lime	10810.81	mol	
mass of lime produced	605.41	kg	1:1 ratio
mass of water required	194.59	kg	1:1 ratio with CaO
mass of limestone required	1081.08	kg	1:1 ratio (neglecting overburden)
mass of carbon dioxide produced	475.68	kg	

Module 5: Clean Backfill Production

lead	239 kg
cadmium	26.7 kg
arsenic	9.8 kg

Module 6: Fly Ash Production

Fly ash is a by-product/waste product from coal combustion. We attribute all fly ash may to the equivalent coal mass.

coal	300 tonnes

Process Energy

PROCESS ENERGY REQUIREMENTS

Module 1: Site Excavation	Volumes of Diesel Fuel Consumed by On-Site Equipment
Module 2: Backfilling	Volumes of Diesel Fuel Consumed by On-Site Equipment
Module 5: Clean Backfill Production	Estimates of Diesel Fuel Consumed by On-Site Equipment During Excavation of Backfill
Module 4: Asphalt Cover Production	Estimates of Diesel Fuel Consumed by On-Site Equipment During Excavation of Mining Aggregate
Module 13: Water Treatment	Pumping over 11000 L of water around the site
Module 8: Hydrated Lime Production	

Module 1: Site Excavation

Volumes of Diesel Fuel Consumed by On-Site Equipment

On-Site Equipment	***Volume of*** **Diesel Consumed (L/vehicle/day) [3]**	**Number of Vehicles [3]**	***Number o*** **Days Operated [**	***Volume of*** **Fuel Consumed (L)**	***Energy Consumed by*** **Excavation Alone (MJ) [4]**
backhoe [1]	350	1	160	56000	2166080
backhoe *[1]*	*350*	*2*	*30*	*21000*	*812260*
dozer [1]	50	1	40	2000	77360
loader [1]	155	1	40	6200	239816

Total: **3295536 MJ**
Precombustion: **362509 MJ**

[1] for soil excavation
[3] MacDonald, pers.comm.
[4] for diesel fuel 38.68 MJ/L ORTEE 1992 (pp. 76)

Module 2: Backfilling

Volumes of Diesel Fuel Consumed by On-Site Equipment

On-Site Equipment	**Volume of Diesel Consumed (L/vehicle/day) [3]**	**Number of Vehicles [3]**	**Number o Days Operated [**	**Volume of Fuel Consumed (L)**	**Energy Consumed by Backfilling Alone (MJ) [4]**
dozer [2]	50	1	40	*2000*	*77360*
vibratory compactor [2]	25	1	80	2000	*77360*

Total: **154720 MJ**
Other: **17019.2 MJ**

[1] for soil excavation
[2] backfilling of excavated site
[3] MacDonald, pers.comm.
[4] for diesel fuel 38.68 MJ/L ORTEE 1992 (pp 76)

Module 5: Clean Backfill Production

Estimates of Diesel Fuel Consumed by On-Site Equipment During Excavation of Backfill

We estimate that this would *involve roughly the same* amount of energy, on a mass basis, as for excavating the contaminated site. Therefore, we consider the backhoe, the dozer and the loader. The diesel consumed is modified on a mass basis.

I.e., multiplied by 67539/62798 = 1.075496035

Backfill	**On-Site Equipment**	**Volume of Diesel Consumed (L/vehicle/day) [3]**	**Number of Vehicles [**	**Number o Days Operated [**	**Volume of** ***Fuel Consumed*** **(L)**	**Transportation** ***Energy Consumed*** **(MJ) [4]**
backhoe	backhoe	376.4236122	1	160	60227.78	2329610
		376.4236122	2	30	22585.42	873603.9
dozer	dozer	53.77480175	1	40	2150 992	83200 37
					0	0
loader	loader	*166.7018854*	1	40	6668.075	257921.2
		350				

Total: **3544336 MJ**
Other: **389876.9 MJ**

Module 4: Asphalt Cover Production

Estimates of *Diesel Fuel Consumed* by On-Site Equipment During Excavation of Mining Aggregate

We estimate that this would involve roughly the same amount of energy, on a mass basis, as for excavating the contaminated site. *Therefore*, we consider the backhoe, the dozer, and the loader. The diesel consumed is modified on a mass basis.

I.e . multiplied by 235/62798 = 0.003742157

Aggregate	**On-Site Equipment**	**Volume of** ***Diesel Consumed*** **(L/vehicle/day) [3]**	***Number o*** **Vehicles [**	**Number o Days Operated [**	**Volume of Fuel Consumed (L)**	**Transportation Energy Consumed (MJ) [4]**
backhoe	backhoe	1.309755088	1	160	209.5608	8105.812
		1.309755088	2	30	78.58531	3039.68
dozer	dozer	0.18710787	1	40	7.484315	289.4933
					0	0
loader	loader	0 580034396	1	40	23.20138	897.4292
					318.8318	
		350				

Total: **12332.41 MJ**
Other: **1356.566 MJ**

Estimates of process energy required to produce asphalt from crude oil

fuel (nat. gas) requirement for feedst	504.32 MJ/m3 of feedstock	
power requirement for feedstock	12.58 kWh/m3 of feedstock	
asphalt binder	26.13 tonnes	
density of asphalt	1150.00 kg/m3	
volume of asphalt	22 72 m3	
feedstock required (30vol% asphalt)	75.72 m3	(feedstock = vacuum residue)
total amount of natural gas required	38189.22 MJ	
total amount of energy attributed to asphalt alone	11456.77 MJ	(rest of energy goes into deasphalted oil production)
precombustion energy (6%)	*687.41 MJ*	
total amount of power required	952 59 kWh	
total amount of power attributed to asphalt alone	285.78 kWh	

Estimates of process energy required to mix asphalt and aggregate

heating oil ratio	9 L/tonne
amount of asphalt mix	261.25 tonnes
total volume of heating oil	2351.25 L
heat content	42.7 MJ/kg
density	0.85 kg/L
energy *use*	85338.62 MJ
precombustion energy	9387.25 MJ
summary of precombustion energ	11446.36 MJ

Energy Summary

diesel (MJ)	12332.41
natural gas (MJ)	11456.77
oil (MJ)	85338.62
coal(MJ)	*757.1935*
nuclear (MJ)	1527.761
hydro (MJ)	332.8725
precombustion (MJ)	11446 36

From electricity generation (I.e after conversion into coal, nuclear and hydro)
15.14387

Module 13: Water Treatment

Pumping over 11000 L of water around the site.

volume pumped	11431.00 m3
density	1000.00 kg/m3
maximum height	6.00 m
pump efficiency	0.77

energy required to pump wastewater to on-site treatment facilities
= volume of wastewater x density of water x g x height/pump efficiency
= 873.80 MJ

To account for the energy lost through use of a generator, an additional energy consumption of 20 % may be assumed
= 174.76 MJ

Bringing the total energy consumption to
= 1048.56 MJ

In addition, there is precombustion energy (e.g. 11% assumed)
= *115.34 MJ*

Therefore the total energy use is
= 1163.91 MJ

Module 8: Hydrated Lime Production

Limestone mining

For the production of limestone 1081.08 kg

		Use Factor	*Production of limestone*		*Precombustion energy*
energy	natural gas	1.30E-02 MJ/kg limestone	14.05 MJ		0.843243 MJ
	diesel	2.10E-02 MJ/kg limestone	22.70 MJ		2.497297 MJ
transport	rail	2.00E-01 t-km/kg limestone	216.22 t-km	51.89189 MJ oil	5.708108 MJ
	truck	2.00E-02 t-km/kg limestone	21.62 t-km	23.78378 MJ oil	2.616216 MJ
	electricity	3.60E-03 kWh/kg limestone	3.89 kWh		
	(mix of nuclear, hyro, coal)				

Lime production

For the production of lime 605.41 kg

		Use Factor	*Production of lime*	*Precombustion energy*
energy	natural gas	2.30E-03 MJ/kg lime	1.39 MJ	0.083546 MJ
	coal	*2.30E-03 MJ/kg lime*	*1.39 MJ*	0.027849 MJ
	electricity	2.80E-02 kWh/kg lime	16.95 kWh	
	(mix of nuclear, hyro, coal)			

Total Ener	115.22	*Total Precombustion*	11.77626 MJ
Total Powe	20.84		

Energy Summary

diesel (MJ)	22.70	
natural gas (MJ)	15.45	
oil (MJ)	75.68	
coal(MJ)	56.62	*55.22626 to generate electricity*
nuclear (MJ)	111.43	111.428 to generate electricity
hydro (MJ)	24.28	24.27821 to generate electricity
precombustion (MJ)	11.78	

Transportation Energy

TRANSPORTATION ENERGY REQUIREMENTS

Transportation between :

Module	*and Module*	*Material transported*
1 and 11	15	hazardous soil
1	14	non-hazardous soil
5	2	clean backfill
13	16	contaminated water
6	11	fly ash
4	3	asphalt
7 and 8	13	water treatment chemicals
13	16	water treatment sludge

Off-site Energy Requirements

(I.e., transportation between modules)
Off-site energy was used for transportation-related activities
Volumes of Diesel Fuel Consumed by *Off-Site Transportation Activities*

	Return Trip Distance [2] (km)	**Number of Return Loads [1] (loads)**	**Average Weight/ return load [1,3] (tonnes/load)**		**Total Weight Moved (tonnes)**	**Energy Consumption Factor [4] (MJ/tonne-km)**	**Transportation Energy Consumption (MJ)**
Transportation of Soil							
Hazardous	614	1523	16.54		50380	0.9	13919994
Non-Hazardous	140	312	19.9		12418	0.9	782334
Clean Backfill	120	2502	13.39		67539	0.9	3647106
Transportation of Water							
Contaminated	210	3	17.97667 [5]		108	0.9	10206
Fly Ash	628	8	18.75		300	0.9	84780
Asphalt	120	7	18.75	262.5	261.25	0.9	14107.5
Water Treatment Chemicals					<1 tonne (neglected)		
Transportation of Sludge							
Water Treatment	614	3	15.75		95	0.9	26248.5

Total = **18484776 MJ**
Already includes precombustion
Transport Energy = **16652951.35 MJ**
Other Energy = **1831824.649 MJ**

[1] from consultant's reports
[2] using road maps
[3] wt/load calculated
assuming density = 2400kg/m3
[4] highway transportation for payloads of 20 tonnes and up (D&T 1991)
includes 11% for crude transportation and refining
[4] approx. 63000 tonnes
excavated from site
[5] 99880 L + 7980 L of contaminated water taken to Quantex in Kitchener in three loads
i.e., 107860 L
Assuming density of water (i.e. this is probably very low),
mass of contaminated water = density * volume
1 tonne/m3 X 107860 L/1000L/m3
107.86 tonnes

Emission Factors

EMISSION FACTORS

Emission		Emission Factors		References
CO2		61.38	(g/tonne-km)	Transport Concepts, 1995 (for 1995 semi-truck vehicle with empty and partial loads (0.65 load factor))
		68.2	(g/MJ)	Calculated from above number using 0.9 MJ/tonne-km conversion for payloads under 20 tonnes
		86.15	(g/tonne-km)	Transport Concepts, 1995 (for 1990 semi-truck vehicle with empty and partial loads (0.65 load factor))
	used	**95.72222**	(g/MJ)	Calculated from above number using 0.9 MJ/tonne-km conversion
		56	(g/tonne-km)	Transport Concepts, 1995 (for 1990 semi-truck vehicle with 100% load factor)
	low	**62.22222**	(g/MJ)	Calculated from above number using 0.9 MJ/tonne-km conversion for payloads under 20 tonnes
		39.9	(g/tonne-km)	Transport Concepts, 1995 (for 1995 semi-truck vehicle with 100% load factor)
		44.33333	(g/MJ)	Calculated from above number using 0.9 MJ/tonne-km conversion for payloads under 20 tonnes
		77.37	(g/MJ)	SACE 1991
		2730	**(g/L fuel)**	**Jaques, 1992 (CO2 Emission Factors based on heavy duty diesel vehicles)**
	for on-site equipment and	**70.57911**	**(g/MJ)**	**Calculated from above number using 38.68 MJ/L conversion**
	off-site transport	**70.68**	**(g/MJ)**	**ORTEE, 1992 (for 1995 - projected - diesel truck with general freight, pp 73)**
		70.68	**(g/MJ)**	**ORTEE, 1992 (for 1990 - diesel truck with general freight pp 73)**
		38.56	(g/tonne-km)	Khan, 1991 (for 1995 projected diesel 48 ft double truck with 100% load factor)
		42.84444	(g/MJ)	Calculated from above number using 0.9 MJ/tonne-km conversion for payloads under 20 tonnes
		51.38	(g/tonne-km)	Khan, 1991 (for 1995 projected diesel 48 ft tractor trailor truck with 100% load factor)
		57.08889	(g/MJ)	Calculated from above number using 0.9 MJ/tonne-km conversion for payloads under 20 tonnes
		45.94	(g/tonne-km)	Khan, 1991 (for 1995 projected diesel B-train double with 100% load factor)
		51.04444	(g/MJ)	Calculated from above number using 0.9 MJ/tonne-km conversion for payloads under 20 tonnes
		56.11	(g/tonne-km)	Khan, 1991 (for 1990 48 ft tractor-trailor with 100% load factor)
		62.34444	(g/MJ)	Calculated from above number using 0.9 MJ/tonne-km conversion for payloads under 20 tonnes
VOC		0.146	(g/tonne-km)	Transport Concepts, 1995 (for 1995 semi-truck vehicle with empty and partial loads (0.65 load factor))
		0.162222	(g/MJ)	Calculated from above number using 0.9 MJ/tonne-km conversion for payloads under 20 tonnes
		0.208	**(g/tonne-km)**	**Transport Concepts, 1995 (for 1990 semi-truck vehicle with empty and partial loads)**
	for on-site equipment	**0.173333**	**(g/MJ)**	**Calculated from above number using 1.2 MJ/tonne-km conversion for payloads under 20 tonnes**
		0.135	**(g/tonne-km)**	**Transport Concepts, 1995 (for 1990 semi-truck vehicle with 100% load factor)**
	for off-site tranport	**0.15**	**(g/MJ)**	**Calculated from above number using 0.9 MJ/tonne-km conversion for payloads under 20 tonnes**
		0.095	(g/tonne-km)	Transport Concepts, 1995 (for 1995 semi-truck vehicle with 100% load factor)
		0.105556	(g/MJ)	Calculated from above number using 0.9 MJ/tonne-km conversion for payloads under 20 tonnes
		0.0529 [1]	(g/MJ)	National Energy Board, 1991 (Cowell)
		0.17	(g/tonne-km)	ORTEE 1992 (for 1995 - projected - diesel truck with general freight pp 73)
		0.19	(g/tonne-km)	ORTEE, 1992 (for 1990 diesel truck with general freight, pp 73)
HC/VOC		0.13	(g/tonne-km)	Khan, 1991 (for 1990 48 ft double truck with 100% load factor)
		0.144444	(g/MJ)	Calculated from above number using 0.9 MJ/tonne-km conversion for payloads under 20 tonnes
CH4		**0.2**	**g/L fuel**	**Trends in Canada's Greenhouse Gas Emissions (1996) Pollution Data Branch, Environment Can**
	for off-site tranport	**0.005171**	**(g/MJ)**	**Calculated from above number using 38.68 MJ/L conversion**
	and for on-site equipment	0.018	(g/MJ)	SACE 1991
NOx		0.55	(g/tonne-km)	Transport Concepts, 1995 (for 1995 semi-truck vehicle with empty and partial loads (0.65 load factor))
		0.611111	(g/MJ)	Calculated from above number using 0.9 MJ/tonne-km conversion for payloads under 20 tonnes
	for on-site equipment	**0.95**	**(g/tonne-km)**	**Transport Concepts, 1995 (for 1990 semi-truck vehicle with empty and partial loads)**
	for off-site tranport	0.791667	(g/MJ)	Calculated from above number using 1.2 MJ/tonne-km conversion for payloads under 20 tonnes
		0.36	(g/tonne-km)	Transport Concepts, 1995 (for 1995 semi-truck vehicle with 100% load factor)
		0.4	(g/MJ)	Calculated from above number using 0.9 MJ/tonne-km conversion for payloads under 20 tonnes
		0.62	(g/tonne-km)	Transport Concepts. 1995 (for 1990 semi-truck vehicle with 100% load factor)
	low	**0.536** [1]	(g/MJ)	National Energy Board, 1991 (Cowell) for medium/heavy duty trucks.
		1.46	(g/tonne-km)	ORTEE 1992 (for 1995 - projected - diesel truck with general freight pp 73)
	high	1.99	(g/tonne-km)	ORTEE, 1992 (for 1990 diesel truck with general freight pp 73)
		0.35	(g/tonne-km)	Khan, 1991 (for 1995 projected diesel 48 ft double truck with 100% load factor)
		0.388889	(g/MJ)	Calculated from above number using 0.9 MJ/tonne-km conversion for payloads under 20 tonnes
		0.47	(g/tonne-km)	Khan, 1991 (for 1995 projected diesel 48 ft tractor trailer with 100% load factor)
		0.522222	(g/MJ)	Calculated from above number using 0.9 MJ/tonne-km conversion for payloads under 20 tonnes
		0.41	(g/tonne-km)	Khan, 1991 (for 1995 projected diesel 48 ft B-train with 100% load factor)
		0.455556	(g/MJ)	Calculated from above number using 0.9 MJ/tonne-km conversion for payloads under 20 tonnes
N2O (nitrous oxide)		**0.4**	**g/L fuel**	**Jaques, 1992 (CO2 Emission Factors based on heavy duty diesel vehicles)**
		0.010341	**(g/MJ)**	**Calculated from above number using 38.68 MJ/L conversion**

particulates		0.0112	(g/tonne-km)	Transport Concepts, 1995 (for 1995 semi-truck vehicle with empty and partial loads (0.65 load factor))
		0.009333	(g/MJ)	Calculated from above number using 1.2 MJ/tonne-km conversion for payloads under 20 tonnes
	for off-site tranport	**0.095**	**(g/tonne-km)**	**Transport Concepts, 1995 (for 1990 semi-truck vehicle with empty and partial loads)**
	and for on-site equipment	**0.079167**	**(g/MJ)**	Calculated from above number using 1.2 MJ/tonne-km conversion for payloads under 20 tonnes
		0.008	(g/tonne-km)	Transport Concepts, 1995 (for 1995 semi-truck vehicle with 100% load factor)
		0.008889	(g/MJ)	Calculated from above number using 0.9 MJ/tonne-km conversion for payloads under 20 tonnes
		0.0082	(g/MJ)	ORTEE 1992 (for 1995 - projected - diesel truck with general freight pp 73)
		0.0074	(g/MJ)	ORTEE, 1992 (for 1990 - diesel truck with general freight, pp 73)
PM		0.0069	(g/tonne-km)	Khan, 1991 (for 1995 projected diesel 48 ft double truck with 100% load factor)
		0.007667	(g/MJ)	Calculated from above number using 0.9 MJ/tonne-km conversion for payloads under 20 tonnes
CO		1.75	(g/tonne-km)	Transport Concepts, 1995 (for 1995 semi-truck vehicle with empty and partial loads (0.65 load factor))
		1.458333	(g/MJ)	Calculated from above number using 1.2 MJ/tonne-km conversion for payloads under 20 tonnes
		2.45	(g/tonne-km)	Transport Concepts, 1995 (for 1990 semi-truck vehicle with empty and partial loads (0.65 load factor))
		2.041667	(g/MJ)	Calculated from above number using 1.2 MJ/tonne-km conversion for payloads under 20 tonnes
		1.14	(g/tonne-km)	Transport Concepts, 1995 (for 1995 semi-truck vehicle with 100% load factor)
		1.266667	(g/MJ)	Calculated from above number using 0.9 MJ/tonne-km conversion for payloads under 20 tonnes
	0.977777778	0.88	(g/tonne-km)	ORTEE 1992 (for 1995 - projected - diesel truck with general freight pp 73)
	1.033333333	0.93	(g/tonne-km)	ORTEE 1992 (for 1990 diesel truck with general freight pp 73)
SO2				
	for off-site tranport	**0.27**	**(g/tonne-km)**	**ORTEE, 1992 (for 1995 - projected - and 1990 diesel truck with general freight, pp 73)**
	for on-site equipment	**0.225**	**(g/MJ)**	**Calculated from above number using 1.2 MJ/tonne-km conversion for payloads under 20 tonnes**
solid waste				
mineral waste		**0.26**	**(kg/t-km)**	S.B. Young's PhD thesis 1996 p84

[1] derived from emission factors for medium/heavy duty trucks in NEB.
Original factors are in g/mil; it has been assumed that they represent 20 tonne trucks
which use energy at a rate of 1.2 MJ/tonne-km

PRECOMBUSTION EMISSIONS This data is taken from S.B. Young's PhD thesis, 1996

FUEL

Air emission factors

	COAL	OIL PRODUCT	NATURAL GAS
	kg/kg coal (1kg=29 MJ)	kg/kg oil (1 kg=45 MJ)	kg/kg gas (1 kg = 54.1)
CO2	2.50E-02	2.80E-01	2.10E-01
methane (and CxHy)	8.70E-03	2.90E-03	2.50E-03
Nox	9.60E-05	2.90E-03	2.70E-03
CO	1.60E-05	8.00E-05	2.00E-04

Solid waste emission factors

mineral waste	5.00E-09	2.20E-03	4.10E-03
ash		2.50E-03	6.00E-04
inert chemicals and industrial waste		4.80E-04	0.00007
dust	5.00E-03		

ELECTRICAL POWER

Assume a 23% coal, 45% nuclear 32% hydro mix.

AIR EMISSION FACTORS

All in kg/kWh

	COAL	NUCLEAR	HYDRO	MIX
CO2	1.00E+00	5.00E-03	2.00E-03	2.33E-01
methane	3.00E-03	4.20E-08	4.00E-05	7.03E-04
Nox	2.70E-03	5.00E-06		6.23E-04
CO	3.00E-04	5.00E-08		7.13E-05

SOLID WASTE EMISSION FACTORS

	COAL	NUCLEAR	HYDRO	MIX
drillings and cuttings	5.30E-01	1.10E-02		1.27E-01
ash	3.36E-02			7.73E-03
waste	3.10E-02			7.13E-03

Process Emissions

PROCESS EMISSIONS

air emissions, solid waste, water emissions

Module 1: Site Excavation	Emissions produced by diesel fuel consumption and precombustion for on-site equipment during excavation
	Emissions from on-site activities - dust and lead emissions
Module 2: Backfilling	Emissions produced by diesel fuel consumption and precombustion for on-site equipment during excavation
Module 5: Clean Backfill Production	Emissions produced by diesel fuel consumption and precombustion for on-site equipment during excavation
Module 4: Asphalt Cover Production	Emissions produced by diesel fuel consumption and precombustion for on-site equipment during aggregate mining
	Emissions produced by asphalt binder production, and processing of asphalt mix
Module 8: Hydrated Lime Production	Emissions for the production of limestone and lime

Module 1: Site Excavation

Emissions produced by diesel fuel consumption and precombustion for on-site equipment during excavation

On-Site Equipment	Fuel Consumed (L)	Transportation Energy Consumption (MJ)	Air Emissions (kg) CO2 [5]	VOCs [6]	CH4 [7]	N2O [8]	particulates [9]	CO [10]	SO2 [11]	NOx [12]
backhoe [1]	56000	2166080	152880	374.73	11.20	22.40	173.29	4418.80	487.37	1713.37
backhoe [1]	21000	812280	57330	140.52	4.20	8.40	64.98	1657.05	182.76	642.51
dozer [1]	2000	77360	5460	13.38	0.40	0.80	6.19	157.81	17.41	61.19
loader [1]	6200	239816	16926	41.49	1.24	2.48	19.19	489.22	53.96	189.69
Total for excavation	79000.00	3295536.00	232596.00	570.13	17.04	34.08	263.64	6722.89	741.50	2606.77
Precombustion energy		362508.96								

Notes:

[5]	2730 g CO2/L diesel fuel
[6]	0.173 g VOC/MJ
[7]	0.2 g CH4/L diesel fuel
[8]	0.4 g N2O/L diesel fuel
[9]	0.08 g/MJ particulates
[10]	2.04 g CO/MJ
[11]	0.225 g SO2/MJ
[12]	0.791 g NOx/MJ

Air Emissions from Precombustion (kg) CO2	NOx	CH4	CO	Solid Waste from Precombustion (kg) mineral waste (kg)	ash (1) (kg)	waste and inert chemicals (kg)
13477.831	139.592	139.592	3.851	105.897	120.338	23.105
5054.187	52.347	52.347	1.444	39.711	45.127	8.664
481.351	4.985	4.985	0.138	3.782	4.298	0.825
1492.188	15.455	15.455	0.426	11.724	13.323	2.558
20505.557	212.379	212.379	5.859	161.115	183.085	35.152

Summary

Energy Consumption (MJ)	Precombustion Energy (MJ)	Total Air Emissions CO2	VOCs	CH4	N2O	NOx	CO	SO2	particulate
3295536.00	362508.96	253101.557	570.128	229.419	34.080	2819.148	6728.752	741.50	263.64

Solid Waste from Precombustion (kg)

mineral waste	ash	industrial waste and inert chemicals
161.115	183.085	35.152

Module 2: Backfilling

Emissions produced by diesel fuel consumption and precombustion for on-site equipment during excavation

On-Site Equipment	Fuel Consumed (L)	Transportation Energy Consumption (MJ)	Air Emissions (kg) CO2 [5]	VOCs [6]	CH4 [7]	N2O [8]	particulates [9]	CO [10]	SO2 [11]	NOx [12]
dozer [2]	2000	77360	5460.00	13.38	0.40	0.80	6.19	157.81	17.41	61.19
vibratory compactor [2]	2000	77360	5460.00	13.38	0.40	0.80	6.19	157.81	17.41	61.19
Total for backfilling	4000.00	154720.00	10920.00	26.77	0.80	1.60	12.38	315.63	34.81	122.38
Precombustion energy		17019.20								

Air Emissions from Precombustion (kg) CO2	NOx	methane	CO	Solid Waste from Precombustion (kg) mineral waste	ash (1)	waste and inert chemicals
481.351	4.985	4.985	0.138	3.782	4.298	0.825
481.351	4.985	4.985	0.138	3.782	4.298	0.825
962.702	9.971	9.971	0.275	7.564	8.596	1.650

Summary

Energy Consumption (MJ)	Precombustion Energy (MJ)	Total Air Emissions CO2	VOCs	CH4	N2O	NOx	CO	SO2	particulate
154720.00	17019.20	11882.70	26.767	10.771	1.600	132.354	315.904	34.81	12.38

Solid Waste from Precombustion (kg)

mineral waste	ash	industrial waste and inert chemicals
7.564	8.596	1.650

Module 5: Clean Backfill Production

Emissions produced by diesel fuel consumption and precombustion for on-site equipment during excavation

On-Site Equipment	Fuel Consumed (L)	Transportation Energy Consumption (MJ)	Air Emissions from Fuel Combustion (kg) CO2 [5]	VOCs [6]	CH4 [7]	N2O [8]	particulates [9]	CO [10]	SO2 [11]	NOx [12]
backhoe	60227.778	2329610.451	164421.83	403.02	12.05	24.09	186.37	4752.41	524.16	1842.72
	22585.417	873603.919	61658.19	151.13	4.52	9.03	69.89	1782.15	196.56	691.02
half-dozer	2150.992	83200.373	5872.21	14.39	0.43	0.86	6.66	169.73	18.72	65.81
				0.00	0.00	0.00	0.00	0.00	0.00	
loader	6668.075	257921.157	18203.85	44.62	1.33	2.67	20.63	526.16	58.03	204.02
Total for backfill produc	91632.262	3544335.901	250156.076	613.170	18.326	36.653	283.547	7230.445	797.476	2803.570
Precombustion energy		389876.9491								

Air Emissions from Precombustion (kg) CO2	NOx	methane	CO	Solid Waste from Precombustion (kg) mineral waste	ash (1)	waste and inert chemicals
14495.354	150.130	150.130	4.142	113.892	129.423	24.849
5435.758	56.299	56.299	1.553	42.710	48.534	9.318
517.691	5.362	5.362	0.148	4.068	4.622	0.887
0.000	0.000	0.000	0.000	0.000	0.000	0.000
1604.843	16.622	16.622	0.459	12.609	14.329	2.751
22053.646	228.413	228.413	6.301	173.279	196.908	37.806

Summary

Energy Consumption (MJ)	Precombustion Energy (MJ)	Total Air Emissions CO2	VOCs	CH4	N2O	NOx	CO	SO2	particulates
3544335.90	389876.95	272209.72	613.170	246.739	36.653	3031.982	7236.746	797.48	283.55

Solid Waste from Precombustion (kg)

mineral waste	ash	industrial waste and inert chemicals
173.279	196.908	37.806

Module 4: Asphalt Cover Production

Emissions produced by diesel fuel consumption and precombustion for on-site equipment during aggregate mining

On-Site Equipment	Fuel Consumed (L)	Transportation Energy Consumption (MJ)	Air Emissions (kg) CO2 [5]	VOCs [6]	CH4 [7]	N2O [8]	particulates [9]	CO [10]	SO2 [11]	NOx [12]
backhoe	209.561	8105.812	572 10	1.40	0.04	0.08	0.65	16.54	1.82	6.41
	78.585	3039.680	214.54	0.53	0.02	0.03	0.24	6.20	0.68	2.40
half-dozer	7.484	289.493	20.43	0.05	0.00	0.00	0.02	0.59	0.07	0.23
	0.000	0.000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
loader	23.201	897.429	63.34	0.16	0.00	0.01	0.07	1 83	0.20	0.71
Total	318.832	12332.414	870.411	2 134	0.064	0.128	0.987	25 158	2 775	9.755
Precombustion energy		1356.565585								

Air Emissions from Precombustion (kg) CO2	NOx	methane	CO	Solid Waste from Precombustion (kg) mineral waste	ash (1)	industrial waste and inert chemicals
50.436	0.522	0.522	0.014	0.396	0.450	0 086
18.914	0 196	0.196	0.005	0.149	0.169	0 032
1.801	0.019	0.019	0.001	0.014	0.016	0.003
0.000	0 000	0.000	0.000	0.000	0.000	0.000
5.584	0.058	0.058	0.002	0.044	0.050	0.010
76.735	0 795	0.795	0.022	0.603	0.685	0.132

Emissions produced by asphalt binder production, and processing of asphalt mix

		Energy Consumption	Precombustion	Air Emissions from Combustion (kg) CO2	CO	N2O	NOx	CH4
energy	natural gas (MJ)	11456.77	687.4059648	687 406	0.229		2 291	0.458
	oil (MJ)	85338.62	9387 248063	58883.647	1 707		64.004	13.654
	electricity (kWh) *(mix of nuclear hyro, coal)*	285.78		66.557	0.006		0.178	0.200
		96795.38	10074 65403	59637.610	1 942	0.000	66.473	14.312

Air Emissions from Precombustion (kg) CO2	NOx	methane	CO	Solid Waste from Precombustion (kg) mineral wa	ash (1)	industrial waste and inert chemicals	drillings and cuttings	ash	waste
44.472	0.571779	0.529425	0.042354034	0.868258	0.127062101	0.0148239			
530.996	5.4996	5.4996	0.1517131	4.17211	4 741034375	0.9102786			
66.554	0.17811		0.020361577	36.25075	2 080453039	2 0375866	36.25075	2.208481	2 037587
642.022	6.249	6.029	0.214	41.291	6.949	2.963	36.25075	2.208481	2 037587

Summary

Energy Consumption (MJ)	Precombustion Energy (MJ)	Total Air Emissions CO2	VOCs	CH4	N2O	NOx	CO	SO2	particulates
109127.80	11431.22	61226.78	2.134	21.200	0.128	83.273	27 336	2 77	0.99

Solid Waste from Precombustion (kg)

mineral waste	ash	industrial waste and inert chemicals	drillings and cuttings
41.894	9.842	5.132	36.2507511

Module 1: Site Excavation

Emissions from on-site activities - dust and lead emissions

		Total Dustfall (g/m2/30 days)	Average Dustfall (g/m2/30 days)	Total Lead in Dustfall (g/m2/30 days)	erage Lead in Dustfall /m2/30 day	Site Area (m2)	Expanded Site Area (m2)	Total Mass o Contaminate (g)	Total Mass of Lead in Dust (g)
Month	1	8.2	7 15	0.02	0.045	14973.4		107059.81	673.803
	1	6.1		0.07					
	2	10.3	7 766666667	0.01	0.023333	14973.4		116293.407	349.3793333
	2	7 3		0.05					
	2	5.7		0.01					
	3	7.4	5.033333333	0.01	0.01	14973.4		75366.1133	149.734
	3	4.1		0 01					
	3	3.6		0.01					
	4	9.08	14.14333333	0.01	0.01	14973.4		211773.787	149.734
	4	25.4		0.01					
	4	7.95		0.01					
	5	4.75	4.71	0.01	0.01	14973.4		70524.714	149.734
	5	4.34		0.01					
	5	5.04		0.01					
	6	4.7	3.523333333	0.01	0.01	14973.4		52756.2793	149.734
	6	2.99		0.01					
	6	2.88		0.01					
	7	7.05	3.393333333	0.01	0.01	14973.4		50809.7373	149.734
	7	1.83		0.01					
	7	1.3		0.01					
	8	5.14	3.31	0.01	0.01	14973.4		49561 954	149.734
	8	1.45		0.01					
	8	3.34		0.01					
	9	8.04	6.443333333	0.01	0.01	14973.4		96478.6073	149.734
	9	4.61		0.01					
	9	6.68		0.01					
	10	1.41	1.08	0.01	0.01	14973 4		16171.272	149.734
	10	0.99		0.01					
	10	0.84		0.01					
	11	0.12	0.083333333	0.01	0.01	14973.4		1247 78333	149.734
	11	0.06		0.01					
	11	0.07		0.01					
	12	4.3	2.56	0.01	0.01	14973.4		38331 904	149.734
	12	1.29		0.01					
	12	2.09		0.01					
	13	4.09	4.465	0.01	0.01	14973.4		66856.231	149 734
	13	4.84		0 01					
	14	6.11	3.286666667	0.01	0.01	14973.4		49212.5747	149 734
	14	2.4		0.01					
	14	1.35		0.01					
	15	8 93	4.83	0.01	0.01	14973.4		72321.522	149.734
	15	3.44		0.01					
	15	2 12		0.01					
	16	6.02	3.07	0.01	0.01	14973.4		45968 338	149.734
	16	1.75		0.01					
	16	1.44		0.01					
	17	10.2	5.016666667	0.01	0.01	14973.4		75116.5567	149.734
	17	2.24		0.01					
	17	2.61		0.01					
	18	3.17	2 103333333	0.01	0.01	14973.4		31494.0513	149.734
	18	1.39		0.01					
	18	1.75		0.01					
	19	3.03	11.21666667	0.01	0 01	14973 4		167951.637	149.734
	19	24.9		0.01					
	19	5.72		0.01					
							g	1395296.28	3568.660333
						Totals:	kg	**1395.29628**	**3.568660333**
								dust	**lead**

Module 8: Hydrated Lime Production

Emissions for the production of limestone and lime

Limestone mining

For the production of limestone 1081 kg

		Energy Consumption	Air Emissions from Combustion (kg) CO2	CO	N2O	NOx	CH4	particulates
energy	natural gas (MJ)	14.05	0.843	0.000		0.003	0.001	
	diesel (MJ)	22.70	15.665	0.000		0.017	0.004	
transport	rail (MJ)	51.89	0.830	0.001	0.016		0.001	0.001
	truck (MJ)	23.78	1.332	0.000	0.015		0.003	0.001
	electricity (kWh) *(mix of nuclear hyro, coal)*	3.89	0.906	0.000		0.002	0.003	
			19.577	0.002	0.031	0.022	0.011	0.002

Air Emissions from Precombustion (kg)				Solid Waste from Precombustion (kg)			*drillings and*		
CO2	methane	NOx	CO	mineral wa	ash (1)	industrial waste and inert chemicals	cuttings	ash	waste
0.055	0.000649	0.000701404	5.2E-05	0.0010651	0.000155868	1.81845E-05			
0.141	0.001463	0.001463063	4.04E-05	0.0011099	0.001261261	0.000242162			
12.085	0.036471	0.032341622	0.003697	6.5824865	0.377772973	0.369989189	0.493686	0.030077	0.027749
12.281	0.039	0.035	0.004	6.585	0.379	0.370			

Lime production

		Energy Consumption	*Air Emissions from Combustion (kg)* CO2	CO	N2O	NOx	CH4
energy	natural gas (MJ)	1.39	0.08355	0.00003		0.00028	0.00006
	coal (MJ)	1.39	0.13924	0.00004		0.00042	0.00042
	electricity (kWh) (mix of nuclear hyro, coal)	*16.95*	*3.94797*	*0.00120*		0.01056	0.01187
			4 17076	0.00127		0.01126	0.01234

Air Emissions from Precombustion (kg)				Solid Waste from Precombustion (kg)			drillings and		
CO2	methane	*NOx*	*CO*	*mineral wasteash (3)*		*industrial waste and inert chemicals*	cuttings	ash	waste
0.005	6.43E-05	6.94929E-05	5.15E-06	0.0001055	1.54429E-05	1.80167E-06			
0.001	1.39	4.60943E-06	7.66E-07	0.2400746					
0.324	0.000979	0.000867834	6.92E-05	0.1766301	0.010136908	0.009928045	2.150279	0.131	0.120663
0.33089	1.39378	0.00094	0.00011	0.41681	*0.01015*	*0.00993*			

Summary

Energy Consumption (MJ)	Precombustion Energy (MJ)	Total Air Emissions CO2	VOCs	CH4	N2O	NOx	CO	SO2	particulates
115.22	11.76	36.36		1.456	0.031	0.069	0.007		0.00

Solid Waste from Precombustion (kg)

mineral waste	ash	industrial waste and inert chemicals	drillings and cuttings
7.001	0.550	0.529	2 643965405

Transportation Emissions

TRANSPORTATION EMISSIONS

OFF-SITE TRANSPORTATION EMISSIONS

air, precombustion, solid waste

	Energy Consumption Factor [4] (MJ/tonne-km)	Transportation Energy Consumption (MJ)	Air emissions associated with fuel combustion (kg) CO2	*VOCs*	*CH4*	*N2O*	particulates	CO
Hazardous	0.9	13919994.000	1332452.759	2938.665	69.600	143.933	1469.333	37893.317
Non-Hazardous	0.9	782334.000	*74886.749*	*165.159*	3.912	8.089	82.580	2129.687
Clean Backfill	0.9	3647106.000	349109.091	769.945	18.236	37 711	384 972	9928.233
Contaminated	0.9	10206.000	976 941	2 155	0.051	0.106	1.077	27.783
Fly Ash	0.9	84780.000	8115.330	17 898	0.424	0.877	8.949	230.790
Asphalt	0.9	14107.500	1350.401	2 978	0.071	0.146	1.489	38.404
Treatment Chemicals	0.9	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Water Treatment Sludge	0.9	26248.500	2512.565	5.541	0.131	0.271	2 771	71.454
	Total =	**18484776.000**	**1769403.836**	**3902.342**	**92.424**	**191.133**	**1951.171**	**50319.668**
			86.15	0.19	0.0045	0.01034	*0.095*	*2.45*

Above emission factors in g/tonne-km (g/MJ)

PRECOMBUSTION EMISSIONS

SO2	NOx	mineral waste (tonnes)	CO2 (kg)	NOx (kg)	methane (kg)	CO (kg)	mineral waste (kg)	ash (kg)	inert chemica (kg)
4175.998	14693.327	4021.332	86613.296	897.066	897.066	24 747	680.533	773.333	148.480
234 700	825.797	226.008	4867.856	50.417	50.417	1.391	38.247	43.463	8.345
1094.132	3849.723	1053.608	22693 104	235.036	235.036	6.484	178.303	202 617	38.902
3.062	10.773	2.948	63.504	0.658	0.658	0.018	0.499	0.567	0.109
25.434	89.490	24.492	*527.520*	*5.464*	*5.464*	0.151	4.145	4 710	0.904
4.232	14.891	4 076	87 780	0.909	0.909	0.025	0.690	0.784	0.150
0.000	0.000	0.000	*0.000*	*0.000*	0.000	0.000	0.000	0.000	0.000
7.875	27.707	7 583	163.324	1.692	1 692	0.047	1.283	1.458	0.280
5545.433	**19511.708**	**5340.046**	**115016.384**	**1191.241**	**1191.241**	**32.862**	**903.700**	***1026.932***	***197.171***
0.27	**0.95**								

Summary

Transportation Energy Consumption (MJ)	Precombustion Energy *(MJ)*	CO2 *(kg)*	VOCs (kg)	CH4 (kg)	N2O (kg)	particulates (kg)	CO (kg)	SO2 (kg)	mineral waste (kg)
16652951.35	1831824.649	1884420.220	3902 342	1283.665	191 133	1951 171	50352 530	*5545.433*	*6243.747*

NOx (kg)	ash (kg)	Inert chemicals and industrial waste (kg)
20702.949	1026.932	197 171

Summary Listings

Summary of Inventory by Module, and by Life Cycle Stage

1 Site excavation
2 Backfilling
3 Capping
4 Asphalt production
5 Clean backfill production
6 Fly ash production
7 PAC production
8 Hydrated lime production
9 Dust Mitigation
10 Monitoring
11 Soil stabilization
12 Monitoring
13 Water Treatment
14 Deposition in non-hazardous landfill
15 Deposition in hazardous landfill
16 Deposition of contaminated water in hazardous landfill

INPUTS

	Modules *Raw Materials Acquisition*						*Site Processing*			
	4	5	6	7	8	**Summary**	1	2	3	**Summary**
crude oil (tonnes)	26.125					**26.125**				0
aggregate (tonnes)	235.125					**235.125**				0
clean soil (tonnes)		67539				**67539**				0
lead (kg)		239				**239**				0
cadmium (kg)		26.7				**26.7**				0
arsenic (kg)		9.8				**9.8**				0
coal (tonnes)			300			**300**				0
sulfur						**0**				0
bauxite						**0**				0
calcium chloride						**0**				0
limestone (kg)					1081.08	**1081.081081**				0
water (kg)					194.59	**194.5945946**				0
water (m3)						**0**				0
						0				0

(continued)

Waste Management							*Transportation between Modules*	*Final Summary*	
11	14	15	16	9	13	**Summary**	**Summary**		
								26.125	**crude oil (tonnes)**
								235.125	**aggregate (tonnes)**
								67539	**clean soil (tonnes)**
								239	**lead (kg)**
								26.7	**cadmium (kg)**
								9.8	**arsenic (kg)**
								300	**coal (tonnes)**
								0	**sulfur**
								0	**bauxite**
								0	**calcium chloride**
								1081.081081	**limestone (kg)**
								194.5945946	**water (kg)**
				3430		**3430**		**3430**	**water (m3)**

ENERGY

	Modules *Raw Materials Acquisition*						*Site Processing*			
	4	5	6	7	8	**Summary**	1	2	3	**Summary**
general fuel (MJ)						**0**				**0**
diesel (MJ)	12332.41	3544335.9			22.70	**3556691.018**	3295536	154720		**3450256**
oil (MJ)	85338.62				75.68	**85414.29443**				**0**
natural gas (MJ)	11456.77				15.45	**11472.21257**				**0**
coal(MJ)	757.19				56.62	**813.8121474**				**0**
nuclear (MJ)	1527.76				111.43	**1639.189235**				**0**
hydro (MJ)	332.87				24.28	**357.150696**				**0**
precombustion (MJ)	11446.36	389876.949			11.78	**401335.0888**	362509	17019.2		**379528.16**

(continued)

Waste Management							*Transportation between Modules*		*Final Summary*	
11	14	15	16	9	13	**Summary**	Btw Modules	**Summary**		
					1048.56	**1048.5641**		**0.00**	**1048.56**	**general fuel (MJ)**
						0	16652951.4	**16652951.35**	**23659898.37**	**diesel (MJ)**
						0		**0.00**	**85414.29**	**oil (MJ)**
						0		**0.00**	**11472.21**	**natural gas (MJ)**
						0			**813.81**	**coal(MJ)**
						0			**1639.19**	**nuclear (MJ)**
						0			**357.15**	**hydro (MJ)**
					115.34	**115.34206**	1831824.65	**1831824.65**	**2612803.24**	**precombustion (MJ)**

AIR EMISSIONS

	Modules *Raw Materials Acquisition*						*Site Processing*			
	4	5	6	7	8	**Summary**	1	2	3	**Summary**
CO2 (kg)	61226.78	272209.72	NA		512.03	**333948.5345**	253101.6	11882.70		**264984.2596**
Sox (kg)	NA	NA	NA		NA	**0**	NA	NA		**0**
NOx (kg)	83.272541	3031.98246	NA		0.068967	**3115.323964**	2819.148	132.35436		**2951.502327**
CO (kg)	27.3361016	7236.74628	NA		0.0075	**7264.089875**	6728.752	315.90386		**7044.656028**
CxHy (kg)	NA	NA	NA		NA	**0**	NA	NA		**0**
particulates (kg)	0.99	283.55	NA		0.002	**284.5354587**	263.64	12.38		**276.02048**
N2O (kg)	0.12753272	36.6529049	NA		0.030832	**36.81127003**	34.08	1.6		**35.68**
CH4 (kg)	21.2000405	246.73921	NA		1.455539	**269.3947899**	229.419	10.770844		**240.1898311**
SO2 (kg)	2.77	797.48	NA		0.00	**800.2503709**	741.50	34.81		**776.3076**
VOC (kg)	2.13350769	613.170111	NA		0	**615.3036185**	570.1277	26.76656		**596.894288**
coarse dust (kg)						**0**	1395.296			**1395.296279**
lead (kg)						**0**	3.56866			**3.568660333**

(continued)

Waste Management							*Transportation between Modules*			*Final Summary*	
11	14	15	16	9	13	**Summary**		**Summary**			
							1884420.22	**1884420.22**	CO2 (kg)	**2483353.01**	CO2 (kg)
								0.00	Sox (kg)	**0.00**	Sox (kg)
							20702.95	**20702.95**	NOx (kg)	**26769.78**	NOx (kg)
							50352.53	**50352.53**	CO (kg)	**64661.28**	CO (kg)
								0.00	CxHy (kg)	**0.00**	CxHy (kg)
							1951.17	**1951.17**	particulates (kg)	**2511.73**	particulates (kg)
							191.13	**191.13**	N2O (kg)	**263.62**	N2O (kg)
							1283.67	**1283.67**	CH4 (kg)	**1793.25**	CH4 (kg)
							5545.43	**5545.43**	SO2 (kg)	**7121.99**	SO2 (kg)
							3902.34	**3902.34**	VOC (kg)	**5114.54**	VOC (kg)
								0.00	coarse dust (kg)	**1395.30**	coarse dust (kg)
								0.00	lead (kg)	**3.57**	lead (kg)

WATERBORNE EMISSIONS

	Modules *Raw Materials Acquisition*						*Site Processing*			
	4	5	6	7	8	**Summary**	1	2	3	**Summary**
water to sanitary sewers										
Fluorine (kg)										
Silver (kg)										
Aluminum (kg)										
Arsenic (kg)										
Cadmium (kg)										
Chromium (kg)										
Copper (kg)										
Iron (kg)										
Lead (kg)										
Phosphorus (kg)										
Zinc (kg)										
BOD (kg)										
TSS (kg)										

(continued)

Waste Management 11	14	15	16	9	13	Summary	Transportation between Modules Summary	Final Summary
					11431	11431		11431.00 water to sanitary sewe
					4.5	4.5		4.50 Fluorine (kg)
					0.05	0.05		0.05 Silver (kg)
					116	116		116.00 Aluminum (kg)
					5.8	5.8		5.80 Arsenic (kg)
					1.6	1.6		1.60 Cadmium (kg)
					0.4	0.4		0.40 Chromium (kg)
					13.5	13.5		13.50 Copper (kg)
					550	550		550.00 Iron (kg)
					91	91		91.00 Lead (kg)
					6.1	6.1		6.10 Phosphorus (kg)
					13	13		13.00 Zinc (kg)
					60	60		60.00 BOD (kg)
					4525	4525		4525.00 TSS (kg)

SOLID WASTE

	Modules *Raw Materials Acquisition* 4	5	6	7	8	**Summary**	*Site Processing* 1	2	3	13	**Summary**
soil as solid waste (tonnes) (non-hazardous)						**0**					0
soil as solid waste (tonnes) (hazardous)						**0**					0
sludge as solid waste (tonnes) (hazardous)						**0**					0
water as solid waste (tonnes) (hazardous)						**0**					0
mineral waste (kg)	41.8940371	173.278644			0.25	**215.4226811**	161 1151	7.5640889			168.6791822
ash (kg)	9.84216457	196.90755			0.01	**206.7597146**	183.0853	8.5955556			191.6808889
inert chemicals and industrial waste (kg)	5.13182139	37 8062496			0	**42.938071**	35.15238	1.6503467			36.80273067
drillings and cuttings (kg)	36.2507511					**36.2507511**					0

(continued)

Waste Management 11	14	15	16	9	13	**Summary**	*Transportation between Modules*	**Summary**	***Final Summary***
	12418					**12418**		**0**	**12418.00** soil as solid waste (tonnes) (non-hazardous)
		50380				**50380**		**0**	**50380.00** soil as solid waste (tonnes) (hazardous)
		95				**95**		**0**	**95.00** sludge as solid waste (tonnes) (hazardous)
			108			**108**			**108.00** water as solid waste (tonnes) (hazardous)
						0			
						0	6243.74656	**6243.74656**	**6627.85** mineral waste (kg)
						0	1026.932	**1026.932**	**1425.37** ash (kg)
						0	197 170944	**197 170944**	**276.91** inert chemicals and industrial wast (kg)
						0		**0**	**36.25** drillings and cuttings (kg)

Final Tables

Final Tables

Inventory Data
Indicator Data: GWP, SWB, GER

INPUTS	***Raw Materials Acquisition***	Distribution %	***Site Processing***	***Waste Management***	Distribution %	***Transportation Between Modules***	***Grand Totals***	INPUTS
crude oil (kg)	2.61E+04	0%	0	0	0%	0	2.61E+04	crude oil (kg)
aggregate (kg)	2.35E+05	0%	0	0	0%	0	2.35E+05	aggregate (kg)
clean soil (kg)	6.75E+07	100%	0	0	0%	0	6.75E+07	clean soil (kg)
lead (kg)	2.39E+02	0%	0	0	0%	0	2.39E+02	lead (kg)
cadmium (kg)	2.67E+01	0%	0	0	0%	0	2.67E+01	cadmium (kg)
arsenic (kg)	9.80E+00	0%	0	0	0%	0	9.80E+00	arsenic (kg)
coal (tonnes)	3.00E+02	0%	0	0	0%	0	3.00E+02	coal (tonnes)
sulfur (kg)	0	0%	0	0	0%	0	0.00E+00	sulfur (kg)
bauxite (kg)	0	0%	0	0	0%	0	0.00E+00	bauxite (kg)
calcium chloride (kg)	0	0%	0	0	0%	0	0.00E+00	calcium chloride (k
limestone (kg)	1.08E+03	0%	0	0	0%	0	1.08E+03	limestone (kg)
water (kg)	1.95E+02	0%	0	3.43E+06	100%	0	3.43E+06	water (kg)
TOTAL	**6.78E+07**	**100%**	**0**	**3.43E+06**	**100%**	**0**	**7.12E+07**	**kg**

ENERGY	***Raw Materials Acquisition***	Distribution %	***Site Processing***	Distribution %	***Waste Management***	Distribution %	***Transportation Between Modules***	Distribution %	***Grand Totals***	ENERGY
general fuel (MJ)	0.00E+00	0%	0.00E+00	0%	1048.564145	90%	0	0%	1.05E+03	fuel (MJ)
diesel (MJ)	3.56E+06	88%	3.45E+06	90%	0	0%	1.67E+07	90%	2.37E+07	diesel (MJ)
oil (MJ)	8.54E+04	2%	0.00E+00	0%	0	0%	0	0%	8.54E+04	oil (MJ)
natural gas (MJ)	1 15E+04	0%	0	0%	0	0%	0	0%	1.15E+04	natural gas (MJ)
coal (MJ)	8.14E+02	0%	0	0%	0	0%	0	0%	8.14E+02	coal (MJ)
nuclear (MJ)	1.64E+03	0%	0	0%	0	0%	0	0%	1.64E+03	nuclear (MJ)
hydro (MJ)	3.57E+02	0%	0	0%	0	0%	0	0%	3.57E+02	hydro (MJ)
precombustion (MJ)	4.01E+05	10%	3.80E+05	10%	115.342056	10%	1.83E+06	10%	2.61E+06	other (MJ)
GER (MJ)	**4.06E+06**	**100%**	**3.83E+06**	**100%**	**1163.906201**	**100%**	**1.85E+07**	**100%**	**2.64E+07**	**MJ**
GER (%)	**15%**		**15%**		**0%**		**70%**		**100%**	***GER (%)***

AIR EMISSIONS	***Raw Materials Acquisition***	Distribution %	*GWP*	Distribution %	***Site Processing***	Distribution %	*GWP*	Distribution %	***Waste Management***	
CO2 (kg)	3.34E+05	96%	3.34E+05	90.6%	2.65E+05	95%	2 65E+05	88.9%	0	
NOx (kg)	3.12E+03	1%			2.95E+03	1%			0	
CO (kg)	7.26E+03	2%	1 45E+04	3.9%	7.04E+03	3%	1.41E+04	4.7%	0	
CxHy (kg)	0.00E+00	0%			0.00E+00	0%			0	
CH4 (kg)	2.69E+02	0%	5.66E+03	1 5%	2.40E+02	0%	5 04E+03	1 7%	0	
N2O (kg)	3.68E+01	0%	7 58E+03	2 1%	3.57E+01	0%	7.35E+03	2 5%	0	
SO2 (kg)	8.00E+02	0%			7.76E+02	0%			0	
VOC (kg)	6.15E+02	0%	6.77E+03	1.8%	5.97E+02	0%	6.57E+03	2.2%	0	
particulates (kg)	2.85E+02	0%			2.76E+02	0%			0	
coarse dust (kg)	0	0%			1.40E+03	1%			0	
lead (kg)	0	0%			3.57E+00	0%			0	
TOTAL (kg)	**3.46E+05**	100%			**2 78E+05**	100%			0	
GWP (kg CO2equiv.)	,		**3.68E+05**	100%			**2.98E+05**	100%		**0.00E+00**
GWP (%)			**13%**				**11%**			**0%**

(continued)

Transportation Between Modules	Distribution %	*GWP*	Distribution %	***Grand Totals GWP***	***Grand Totals*** AIR EMISSIONS	
1.88E+06	96%	1.88E+06	90%	2.48E+06	2.48E+06	CO2 (kg)
2 07E+04	1%				2 68E+04	Nox (kg)
5.04E+04	3%	1.01E+05	5%	1.29E+05	6.47E+04	**CO (kg)**
0.00E+00	0%				0.00E+00	CxHy (kg)
1.28E+03	0%	2.70E+04	1%	3.77E+04	1 79E+03	**CH4 (kg)**
1.91E+02	0%	3.94E+04	2%	5.43E+04	2.64E+02	**N2O (kg)**
5.55E+03	0%				7 12E+03	SO2 (kg)
3.90E+03	0%	4.29E+04	2%	5.63E+04	5.11E+03	**VOC (kg)**
1 95E+03	0%				2.51E+03	particulates (kg)
0.00E+00	0%				1.40E+03	coarse dust (kg)
0.00E+00	0%				3.57E+00	lead (kg)
1.97E+06	100%				2.59E+06	***TOTAL (kg)***
		2.09E+06	100%	**2.76E+06**		***GWP (kg CO2equiv.)***
		76%		**100%**		***GWP (%)***

WATERBORNE EMISSIONS	Raw Materials Acquisition	Site Processing	Distribution %	Waste Management		Transportation Between Modules	Grand Totals	WATERBORNE EMISSIONS
water to sewers (kg)	0			1.14E+07	NA	0	1.14E+07	water to sanitary sew
Fluorine (kg)	0			4.50E+00	1%	0	4.51E+00	Fluorine (kg)
Silver (kg)	0			5.00E-02	0%	0	5.01E-02	Silver (kg)
Aluminum (kg)	0			1.16E+02	14%	0	1.16E+02	Aluminum (kg)
Arsenic (kg)	0			5.80E+00	1%	0	5.81E+00	Arsenic (kg)
Cadmium (kg)	*0*			*1.60E+00*	*0%*	*0*	*1.60E+00*	*Cadmium (kg)*
Chromium (kg)	0			4.00E-01	0%	0	4.00E-01	Chromium (kg)
Copper (kg)	0			1.35E+01	2%	0	1.35E+01	Copper (kg)
Iron (kg)	0			5.50E+02	69%	0	5.51E+02	Iron (kg)
Lead (kg)	0			9.10E+01	11%	0	9.11E+01	Lead (kg)
Phosphorus (kg)	0			6.10E+00	1%	0	6.11E+00	Phosphorus (kg)
Zinc (kg)	0			1.30E+01	2%	0	1.30E+01	Zinc (kg)
BOD (kg)	0			6.00E+01	NA	0	6.00E+01	BOD (kg)
TSS (kg)	0			4.53E+03	NA	0	4.53E+03	TSS (kg)
TOTAL	0			5.39E+03	100%	0	**5.39E+03**	**emissions only (kg**
				***does not include water to sewers**	***does not include water, BOD, TSS**		**1.14E+07**	**water only**
				total =	**8.02E+02**		**1.14E+07**	**total**

SOLID WASTE	Raw Materials Acquisition	Distribution %	Site Processing	Distribution %	Waste Management	Distribution %	Transportation Between Modules	Distribution %	Grand Totals	SOLID WASTE
soil as SW (kg) (non-hazardous)	0	0%	0	0%	1.24E+07	20%	0	0%	1.24E+07	soil as solid waste ((non-hazardous)
soil as SW (kg) (hazardous)	0	0%	0	0%	5.04E+07	80%	0	0%	5.04E+07	soil as solid waste (*(hazardous)*
sludge as SW (kg) (hazardous)	0	0%	0	0%	9.50E+04	0%	0	0%	9.50E+04	sludge as solid wast (hazardous)
water as SW (kg) (hazardous)	0	0%	0	0%	1.08E+05	0%	0	0%	1.08E+05	water as solid waste (hazardous)
mineral waste (kg)	2.15E+02	43%	1.69E+02	42%	0	0%	6.24E+03	84%	6.63E+03	mineral waste (kg)
ash (kg)	2.07E+02	41%	1.92E+02	48%	0	0%	1.03E+03	14%	1.43E+03	ash (kg)
inert chemicals and industrial waste (kg)	42.938071	9%	3.68E+01	9%	0	0%	1.97E+02	3%	2.77E+02	inert chemicals and industrial waste (kg)
drillings/cuttings (kg)	3.63E+01	7%	0.00E+00	0%	0	0%	0	0%	3.63E+01	drillings and cuttings
SWB (kg)	***5.01E+02***	*100%*	***3.97E+02***	*100%*	***6.30E+07***	*100%*	*7.47E+03*	*100%*	***6.30E+07***	***SWB (kg)***
SWB (tonnes)	5.01E-01		3.97E-01		6.30E+04		7.47E+00		6.30E+04	***SWB (tonnes)***
SWB ALL (%)	0%		0%		100%		0%		100%	***SWB ALL (%)***
SWB NO SOIL (%)	6%		5%		0%		89%		100%	***SWB NO SOIL (%)***

BALANCE SUMMARY

INPUTS	7.12E+07	**everything in (kg)**	
OUTPUTS	1.40E+03	coarse dust (kg)	
	3.57E+00	lead (kg)	
	1.14E+07	water to sanitary sewers (kg)	
	5.39E+03	waterborne emissions only (kg)	
	6.30E+07	solid waste not from transportation (kg)	
	7.44E+07	***everything out (kg)***	*105%*

	Raw Materials Acquisition	Site Processing	Waste Managemen	Transportation Between Modules	
Inputs (kg)	6.78E+07	0	3.43E+06	0	
Energy (MJ)	4.06E+06	3.83E+06	1163.9062	1.85E+07	
Air Emissions (kg)	3.46E+05	2.78E+05	0	1.97E+06	
Waterborne Emissions (kg)	0	5.39E+03	#REF!	0	***does not include water**
Solid Waste (kg)	5.01E+02	397.162802	6.30E+07	7.47E+03	

INDICATOR SUMMARY

Values

		Raw Materials Acquisition	Site Processing	Waste Management	Transportation Between Modules
GWP	(kg CO2 equiv.)	3.68E+05	2.98E+05	0.00E+00	2.09E+06
GER	(MJ)	4.06E+06	3.83E+06	1.16E+03	1.85E+07
SWB (1)	(tonnes)	5.01E-01	3.97E-01	6.30E+04	7.47E+00
SWB (2)	(tonnes)	5.01E-01	3.97E-01	NA	6.30E+04

Note: SWB(1) includes all solid waste
SWB (2) excludes all soils and sludges

Percentage

	Raw Materials Acquisition	Site Processing	Waste Management	Transportation Between Modules
GWP	13%	11%	0%	76%
GER	15%	15%	0%	70%
SWB (1)	0%	0%	100%	0%
SWB (2)	6%	5%	0%	89%

Sensitivity Analysis: Parameters Investigated

The following areas are considered:

		Variation			
A - Input Data					
A1	clean backfill	-10%	60785.1	67539	
A2		+10%	74292.9		
A3	hazardous soil	-10%	45342	50380	
A4		+10%	55418		
A5	non-hazardous soil	-10%	11176.2	12418	
A6		+10%	13659.8		
A7	thickness of asphalt cover	-10%	45	50	
A8		+10%	55		
A9	hydrated lime	-50%	400	800	
A10		+10%	880		
A11		+100%			
B - Return Trip Distances					
B1	return trip distance	-10%	552.6	614	
B2	to hazardous landfill	+10%	675.4		
B3	return trip distance	-10%	108	120	
B4	to clean backfill	+10%	132		
C - Energy Consumption Factors					
C1	energy consumption	-10%	0.81	0.9	
C2	factor per tonne-km	+10%	0.99		
C3	backhoe fuel consumption	-10%	315	350	
C4	per vehicle/day	+10%	385		
C5	fuel use by asphalt mixer	-10%	8.1	9	
C6		+10%	9.9		
D - Air Emission Factors					
D1	CO2 minimum	-35%	56 (g/tonne-km)		62.22222 (g/MJ)
D2		-10%	77.535 (g/tonne-km)		77.535 (g/MJ)
D3	CO2 maximum	10%	94.765 (g/tonne-km)		115.8239 (g/MJ)
D4	NOx minimum	-49%	0.4824 (g/tonne-km)		0.536 (g/MJ)
D5		-10%	0.855 (g/tonne-km)		0.7125 (g/MJ)
D6		10%	1.045 (g/tonne-km)		0.870833 (g/MJ)
D7	NOx maximum	52%	1.99 (g/tonne-km)		2.211111 (g/MJ)
D8	CO minimum	-62%	0.93 (g/tonne-km)		1.033333 (g/MJ)
D9		-10%	2.205 (g/tonne-km)		2.205 (g/MJ)
D10	CO maximum	10%	2.695 (g/tonne-km)		3.293889 (g/MJ)

7. Glossary

Accessibility-the manner in which the data are stored or recorded. The data may be stored on hard copy or electronically. The term also refers to the availability of the data to the users; some data may be proprietary.

Ancillary material-a material that is used by the manufacturing system producing a product but is not used directly in the formation of the product.

Atmospheric emissions-residual discharges of emissions to the air (usually expressed in pounds or kilograms per unit output). Includes point sources such as stacks and vents as well as area sources such as storage piles.

Background concentration-the ambient concentration of a chemical in the soil, groundwater, air or sediment in the local environment, which is representative or typical of the conditions in urban or rural setting.

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

Completeness-the percentage of data made available for analysis compared to the potential amount of data in existence.

Composite data-data from multiple facilities performing the same operation that have been combined or averaged in some manner.

Consistency-a qualitative measure of how uniformly the study method is applied to the various components of the analysis. This includes technical details on how the data were collected or measured. It includes the framework from which the data were collected and the way the data values were calculated.

Contaminant-any solid, liquid, gas, odour, heat, sound, vibration, radiation or combination of any of these resulting directly or indirectly from human activities that may cause an adverse effect.

Conversion models-models that characterize and possibly estimate the magnitude of measurement endpoints based on the level of the associated stressor. An example of a conversion model is the Mackay Unit World Model, a generic computer fate-and-exposure model that characterizes the partitioning and transformations of chemical substances introduced into a hypothetical 1 km^3 "ecosystem box."

Co-product-a marketable by-product from a process. This includes materials that may be traditionally defined as waste such as industrial scrap that is subsequently used as a raw material in a different manufacturing process. Note: In life-cycle assessment, by-products are treated as co-products. By-product is defined as a useful product that is not the primary product being produced.

Co-product allocation-adjustment of material inputs, energy requirements, and environmental emissions from a process, activity, or service to (equitably) allocate those impacts attributable to the output product being considered.

Data manipulation-composing the unit operation data sets out of the elementary data. Elementary data may need to be normalized to meet the rate of the selected reference product.

Endpoint-an effect on a human or ecological receptor that can be measured and described in some quantitative fashion.

Ecological receptor-a non-human organism identified as potentially experiencing adverse impacts from exposure to a contaminant, either directly through contact or indirectly through food chain transfer.

Energy characterization-classification of energy according to primary fuel source: wood, natural gas, petroleum, coal, nuclear, hydropower.

Energy of material resource-the fuel value of the raw materials used to make a product. The inherent energy in a product made from a raw material used as fuel supply. Also known as latent energy.

Energy profile-a listing of the energy usage for a system by stage and/or by source. See also energy characterization.

Environmental release-emissions or wastes discharged to the air, land, or water. Contaminants that cross a system boundary into the environment

Exposure-the contact between a contaminant and an individual or population. The exposure may occur through pathways such as ingestion, dermal absorption or inhalation.

Fuel-related wastes-those materials or emissions generated during the combustion of fuels for the production of heat, steam, electricity, or energy to power processes and transportation equipment that are not a component of the usable product or co-products.

Fuel unit-weight or volume of fuel such as litres of fuel oil, kilograms of coal, or cubic metres of natural gas.

Fugitive emissions-emissions resulting from processing, material storage, and handling activities that are difficult to measure and do not flow through pollution control devices; for example, leaks from valves or leaks in process equipment

GER-Gross Energy Requirement.

Global warming-the hypothesis that certain atmospheric constituents are causing an increase in the earth's average temperature.
Greenhouse effect-the hypothesis that certain atmospheric gases trap heat in the earth's atmosphere, leading to global warming.

Greenhouse gas-an atmospheric constituent, such as carbon dioxide, that is thought to contribute to the greenhouse effect

GWP- Global Warming Potential (100 year time horizon unless stated otherwise). The potential of greenhouse gases to contribute to the greenhouse effect, normalized according to CO_2.

Impact-a change to the environment, and the associated consequences for both humans and other ecosystem components, caused directly by the activities of a product or service development and production. Impacts include secondary and tertiary consequences with direct upstream links to primary changes to environmental systems.

Impact assessment-a process to determine the magnitude and significance of environmental impacts within the confines of the goals, scope, and objectives defined in the life-cycle assessment. The investigation of the environmental consequences of energy and natural resource consumption and waste releases associated with an actual or proposed action. It is used to identify and quantify the elements and processes involved in translating (whether through physical or psychological transmission) impact indicators into the response of environmental receptors and the associated impacts incurred by the receptors and suffered within the process of transmission.

Impact chain-the conceptual, qualitative linking of life-cycle inventory items to potential direct and indirect impacts. For instance, NO_x emissions listed in the life-cycle inventory may be linked to acid precipitation, which in turn may be linked to tree damage, acidification of lakes, loss of aquatic and terrestrial biodiversity, soil leaching, and corrosion of materials.

Impact descriptor-a measure or set of significant environmental attributes associated with a particular stressor or stressor category. For example, a CO_2 emissions value from a life-cycle inventory could be run through the appropriate conversion model to yield the potential contribution to global warming.

Impact indicator-a representation of substance or action that has the potential for environmental impact or harm. Also, a surrogate measure of potential environmental impacts, that can be expressed in a relatively simple, perhaps quantitative format. As an indicator, its meaning is constrained by the assumptions, measures and calculations used in its construction.

Practical impact indicators (PII)-generally accepted indicators that are used to assess the environmental significance and effects of the environmental burdens associated with the life cycle of the product.

Selected impact indicators (SII)-practical impact indicators rationalized in accordance with the initiation (goal-seeking) phase by adding Additional Relevant Indicators (ARI) and removing Disregarded Impact Indicators (DII). ARIs are those indicators that may be necessary for the particular application. DIIs are those indicators that may not be germane or may be waived for the application.

SII = PII +ARI – DII

Improvement assessment-the component of a life-cycle assessment that is concerned with the evaluation of opportunities to affect reductions in environmental releases and resources.

Indirect impact-a potential impact that is not directly attributable to a life-cycle inventory item, but rather stems from another impact. Indirect impacts may also interact with the environment causing further indirect impacts. For example, human lung damage and aesthetic nuisance could be indirect impacts of photochemical smog, which is a direct impact of ozone emissions.

Industrial solid waste-includes wastewater treatment sludges, solids from air pollution control devices, trim or scrap materials that are not recycled, fuel combustion residues (such as the ash generated by burning wood or coal), and mineral extraction residues.

Landfill-

Non-hazardous landfills-sanitary land disposal sites for non-hazardous solid waste at which the waste is spread in layers, compacted to the smallest practical volume, and cover material applied at the end of each operating day.

Hazardous landfills-secure disposal sites for hazardous waste. They are selected and designed to minimize the chance of release of hazardous substances into the environment.

Life cycle-the stages of a product, service, or activity's life, beginning with raw materials acquisition, continuing through processing, materials manufacture, product fabrication and use, and concluding with any of a variety of waste management options. This includes transportation.

Life-cycle assessment (LCA)-a concept and a method to evaluate the environmental effects of a product or activity holistically, by analyzing its entire life cycle. This includes identifying and quantifying energy and materials used, and wastes released to the environment, assessing their environmental impact, and evaluating opportunities for improvement. The life-cycle assessment consists of four complementary components-initiation, inventory, impact, and improvement

Life-cycle inventory-the identification and quantification of energy, resource usage, and environmental emissions for a particular product, service, or activity.
Life-cycle stages-the set of major sequential stages that a product or service passes through over the course of its existence from cradle to grave. For all products, four generic stages apply: raw materials and energy acquisition, manufacturing (including materials manufacture, product fabrication, and filling / packaging / distribution steps), use / reuse / maintenance, and recycle and waste management

Mass balance-mathematical expression in which a summation of all material inputs to a system is equated to a summation of all outputs, accounting for transformation into energy.

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

Measurement endpoint-a measurable response to a stressor that may act as a surrogate measure, quantitative or qualitative, for a related assessment endpoint. For example, acid precipitation could be a possible measurement endpoint for the assessment endpoint of "lost recreation revenue at lake X" that is indirectly attributable to NO_x emissions. A more direct but difficult measurement endpoint for this scenario could be the lost recreation revenue at lake Y due to NO_x emissions.

National electricity grid-the electricity generated by individual generating stations that are interconnected to form provincial grids and ultimately a national grid.

Peer review-critical review of analysis by experts.

Precombustion energy-energy required to extract, transport, and process the fuels used for power generation. Includes adjustment for inefficiencies in power generation and for transmission losses. Also known as energy of fuel acquisition

Primary data-data or information directly obtained from individual companies or sources.

Primary data gathering-searching and recording elementary data in different data sources. Unit operation data sets are built based on elementary data.

Primary energy raw materials-natural gas, petroleum, coal, nuclear, hydro, and so forth.

Process emissions-waste materials generated or produced from the raw materials, reactions, processes, or related equipment inherent to the process.

Process energy-the energy required for each subsystem for process requirements. These are quantified in terms of fuel or power units such as litres of distillate oil, cubic metres of natural gas, or joules of electricity.

Raw materials-the total inputs for a subsystem including all material present in the product and material found in losses due to emissions, scrap and off-spec products, and no-emission losses (such as moisture due to evaporation). Water is not always a raw material input because it is often removed during a drying step. Includes a primary or secondary (e.g., recovered and/or recycled) feedstock that is used in a subsequent manufacturing process.

Reference dose-an estimate of a daily exposure (mg/kg/day) to the general human population, including sensitive sub-groups, that is likely to be without an appreciable risk of deleterious effects during a lifetime of exposure.

Representativeness-the state of having a sample that is characteristic of a group or population of operations or processes

Risk assessment-the estimation of the nature and probability of the magnitude of risk to human and/or other receptors resulting from exposure to contaminant(s).

Secondary data-published or unpublished data reflecting the results of previous data collection and analyses (e.g., those obtained from published sources in the form of data bases, industry or government publications, journals, or books).

Sensitivity analysis-a systematic evaluation process for describing the effect on the output of variations of inputs to a system.

Soil-loose or unconsolidated material resulting from the breakdown of rock or organic matter by natural physical, chemical and biological processes and which is capable of supporting plant growth. More than 50% of the material by volume must have a particle size of less than 2 mm.

Soil-like-material meeting the above definition of soil except that it need not be a result of natural processes nor need it be capable of supporting plant growth or have a grain size limitation.

Solid waste-solid products or materials disposed of in landfills, incinerated, or composted. Can be expressed in weight or volume terms.

Spill-when used with reference to a pollutant, means a discharge,
a) into the natural environment;
b) from or out of a structure, vehicle, or other container; and
c) is abnormal in quality or quantity in light of all the circumstances of the discharge.
It has a corresponding meaning when used as a verb.
Stressors-conditions that may bring about change, positive or negative, in the environment

Subsurface soil-soil that is more than 1.5 metres from the soil surface, excluding the thickness of any non-soil surface treatment such as asphalt, concrete or aggregate.

Surface soil-soil that is 1.5 m or less from the soil surface, excluding the thickness of any non-soil surface treatment such as asphalt, concrete or aggregate.

System-a collection of operations that perform a desired function. In a life-cycle inventory, the scope of the system is defined by the boundary conditions.

SWB-Solid Waste Burden. Total amount of solid waste resulting from life-cycle activities.

Teratogenicity-the ability of a chemical to cause a change in the normal development process of an unborn organism, resulting in permanent alterations in the biochemical, physiological or anatomical functions of the organism.

Threshold-the concentration or dose of a chemical below which an adverse impact is not expected to occur.

Transparency-the degree to which aggregated data can be traced back to the original values. Clear documentation of primary sources and/or aggregation methods is essential.

Transportation energy-energy required to transport materials and products throughout the process and to final distribution to the consumer. This is converted from the conventional units of "ton-miles" by each transport mode (e.g., truck, rail, barge, airfreight, pipeline, etc.) to energy units using the average efficiency of each mode.

Unit Process-an individual process (subsystem) that is a part of the defined system.

Volatilization-the process by which a chemical converts from a liquid or solid phase into a gaseous phase and disperses into the air.

Waste-an output with no marketable value that is disposed of to the environment. Any material released to the environment through air, water, and land, and has no beneficial use.

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

Waterborne wastes-discharges of pollutants to water (usually expressed in kilograms per unit output) after treatment processes.