ABSTRACT

SUSTAINABLE SITE REMEDIATION: A LIFE CYCLE ASSESSMENT APPROACH

by

Harnoor Dhaliwal

Remediation of contaminated areas is often a resource-intensive activity that itself can create environmental burdens. Life cycle assessment (LCA) was used as a tool to examine the environmental impacts associated with remediation activities. A hypothetical contaminated site with five remediation alternatives was developed for this analysis. The results of Life cycle Impact Assessment (LCIA) indicated that greater site activity in terms of transportation, material and equipment use translated into higher environmental impacts.

A sensitivity analysis was performed to evaluate the environmental impacts further in different time horizons. The results showed that choice of time horizon can have a significant effect on the magnitude of impacts and the interpretation of results. Additionally, it was found that LCA presently has important limitations related to the characterization of certain emissions. It is concluded that LCA as a tool is insufficient for addressing sustainability completely; it should be supplemented with other approaches.

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A LIFE CYCLE ASSESSMENT APPROACH

by
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SUSTAINABLE SITE REMEDIATION:
A LIFE CYCLE ASSESSMENT APPROACH

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I dedicate this thesis to my family.

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GLOSSARY

Afcfee	Air Force Center for Environmental Excellence
AfrS	Methodology for Remediation Selection
ADP	Abiotic Depletion Potential
AP	Acidification Potential
BTEX	Benzene, Toluene, Ethylbenzene and Xylene
CML	Centre of Environmental Science – Leiden University
EP	Eutrophication Potential
FAETP	Freshwater Aquatic Ecotoxicity Potential
GWP	Global Warming Potential
HTP	Human toxicity potential
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for standardization
ITRC	Interstate Technology & Regulatory Council
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCM	Life Cycle Management
MAETP	Marine Aquatic Ecotoxicity Potential
NJSSI	New Jersey Sustainable State Institute
ODP	Ozone Depletion Potential
PM	Particulate Matter
PCOP	Photochemical Oxidation Potential
S/S	Solidification/Stabilization
SARA	Superfund Amendment and Reauthorization Act
SETAC	Society of Environmental Toxicology and Chemistry
SPL	Spill Pot Lining
TETP	Terrestrial Ecotoxicity Potential
TNO	Environment, Energy and Process Innovation
TPH	Total Petroleum Hydrocarbons
US EPA	United States Environmental Protection Agency
USES	Uniform System for the Evaluation of Substances
WMO	World Meteorological Organization

CHAPTER 1

INTRODUCTION

1.1 Background

Contaminated sites are a common occurrence in the United States and most of the world. These sites present a controversial and complex environmental problem. Health and environmental risk, liability, social equity, as well as appropriate and reliable remediation technology are some important aspects of the problems associated with contaminated areas (Soesilo and Wilson, 1997).

Remediation of contaminated sites is often governed by considerations of statutory compliance, cost, social acceptance and technical suitability. Until recently there had been little recognition of the range of impacts caused by remediation itself. Clean up activities are often resource-intensive; while they remove contamination from a localized area they can often create problems like resource depletion, global warming, and emissions to air and water on a larger geographical and temporal scale (Diamond et al., 1999).

In the United States, the use of innovative technologies has been encouraged to return contaminated sites to a productive use. The Superfund Amendment and Reauthorization Act, 1986 (SARA) encourages remedy of contamination by means other than the practice of excavation and disposal or containment. While redevelopment in the US has focused on encouraging economic and social redevelopment by clean up through innovative technologies (US EPA, 2001; US EPA, 1999a), the environmental impact of remediation has received little attention.

In its recent efforts, EPA has recognized the need to incorporate environmental concerns in remediation practices. EPA's Technology Innovation Program has introduced "Green Remediation" (US EPA, 2008) to encourage sustainable practices such as:

- Efficiency in energy use
- Reduction in resource utilization
- Reduction of pollution
- Reduction of waste/ Recycling

An initial set of best management practices has been created to provide building blocks for sustainable remediation (US EPA, 2008). An important component of a sustainable outlook for remediation of contaminated areas is therefore consideration of environmental impacts of the remediation activities.

A number of tools for measuring and monitoring sustainable development have been built in the past, for example, Ecological Footprint (Rees and Wackernagel, 1994), Sustainable Technology Development (Weaver et al., 2000) and Natural Capitalism (Hawken and Lovins, 1999). Life Cycle Assessment (LCA) is one such approach. It has been applied to quantify environmental emissions throughout the life of products and services to achieve sustainable solutions. Impact assessment in LCA is based on a wide spatial and temporal scale where results are presented in relation to a functional unit. (ISO 14040, 1997; Guinée et al., 2002). A functional unit is a specific "function" performed by the product or the product system, which can be used as the basis to compare alternative choices and quantify environmental concerns (Guinée et al., 2002).

Many authors have used the LCA perspective to quantify and assess "secondary impacts" (Volkwein et al., 1999) associated with materials and services used for remediation. Diamond et al. 1999 introduced an LCM (Life Cycle Management) approach - a framework derived from LCA, to provide a qualitative understanding of impacts associated with remediation, where potential impacts are distinguished into three main categories, viz., pollution, disturbance and depletion. This approach was used in a quantitative study to quantify impacts of an excavation and disposal scenario (Page et al., 1999). Solid waste production, land-use impacts and energy consumption (due to off-site transportation) were identified as important environmental issues within a time boundary of 25 years.

LCA has also been used in site remediation studies as a tool to compare practicable options (Harbottle et al., 2007; Blanc et al., 2004; Cadotte et al., 2007; Godin et al., 2004). Harbottle et al., 2007, compared excavation and off-site disposal with stabilization/solidification (S/S). LCA was used to assess impacts and assign scores to four categories in a multi-criteria analysis: human health and safety, local environment, stakeholder concern, future site use and global environment. The study did not conclude that one option was better than the other because of the limited number of parameters considered, but the manufacture of cement in the case of S/S and the transportation for landfilling were identified as the main sources of environmental impact. Another study compared five treatment options for a sulfur contaminated soil (Blanc et al., 2004). LCA was used to guide the selection with respect to resource utilization. The results indicated that treatment options requiring less resources were environmentally more suitable. However, these results were based on short term evaluation of options because the fate of emissions was not taken into account.

Cadotte et al., 2007 compared in-situ and ex-situ treatment scenarios for a diesel-fuel contaminated site. The study included both primary and secondary impacts while also considering the treatment time. It was concluded that the remediation options requiring a long treatment time produced low environmental impact, and the options with short treatment time had relatively higher impacts. Also, the impact assessment identified aquatic ecotoxicity to be most the impacted category. A study by Godin et al., 2004 compared four scenarios to treat an SPL (spent pot lining) - aluminum refining waste landfill. While also identifying ecotoxicity as most dominant; it concluded that LCA can be useful as a "screening tool" for impacts. Ecotoxicity has also been identified as a significant impact in bioremediation of diesel-fuel contaminated soil (Toffoletto et al., 2005).

Although LCA is a tool widely used to assess environmental impacts, there are certain unresolved issues that can affect the decision making. Time horizon is one such issue that is being realized as important in impact assessment results (Huijbregts et al., 2001). Life Cycle Impact Assessment (LCIA) methods typically use a steady state approach where the fate of emissions is calculated with an infinite time horizon (Guinée et al., 1996; Huijbregts et al., 2000b; Hertwich et al.,1998). While the underlying rationale is to capture the long term "potential impacts", the use of an infinite time period is a currently debated subject for reasons such as high uncertainty related to long term impacts. Additionally, some authors have pointed out that using an infinite time horizon can be misleading because an indefinite future is "unknowable" (Cohen, 1995).

The question of temporal scale becomes particularly relevant as the LCA approach is often associated with achieving sustainability goals. Sustainable

Development was defined by the Brundtland Commission as: "To meet the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland Commission, 1987). The question of future or time horizon therefore becomes an important one considering that it is one of the foundations of sustainability.

This work applies the LCA approach to site remediation to assess the secondary impacts and evaluate the usefulness of LCA as a tool to achieve environmental sustainability goals as a result of remediation activities. Relevant sustainability goals have been defined by many organizations in the past. Eleven goals and forty-one indicators of sustainability have been developed for the State of New Jersey (NJSSI, 2004), with an aim to address the three components of sustainable development: society, economy and environment. This study has attempted to align the environmental indicators with a set of ten environmental impact potentials identified as baseline (Guinée et al., 2002).

The recommended baseline impact categories include a number of time dependent categories such as global warming, human and eco-toxicity, ozone depletion, acidification and eutrophication. It is important to assess not only their magnitude but also to understand the effect of temporality, the nature of underlying characterization and any weaknesses in the life-cycle approach to realistically assess the possible environmental problems associated with site remediation.

1.2 Objectives

The objective of this thesis is to apply LCA approach to a set of five remediation options created for a hypothetical contamination situation in order to quantify their secondary impacts. The LCA approach is used as a tool to help understand how best to achieve environmental sustainability goals in site remediation activities. Process contribution and scenario analysis is performed to identify the potential areas within the Life Cycle of remediation activities that lead to emissions and to evaluate the sensitivity of impacts to different time horizons respectively.

The results of this work are intended to be used for optimization of remediation design through identification of major sources of impacts. Reduction of environmental impacts serves as the broader context of this study. While the secondary impacts that arise at larger geographical and temporal scales during remedial actions are important for overall sustainability evaluation, the primary environmental impacts (those that occur at the site due to contamination), on sustainability metrics, are crucial components as well (Toffoletto et al., 2005). The scope of this work is limited to analysis of the secondary impacts. Consideration of the relationships between the primary and secondary impacts is expected to be part of further work.

A hypothetical site with hydrocarbon contamination served as the base for this assessment. The assessment of impacts was performed by using the CML 2 baseline (2000) impact assessment method. Further, a sensitivity analysis was performed to assess the sensitivity of these impacts to different time horizons.

The objective is specified further through consideration of the following questions:

- What are the secondary impacts related to the selected remediation options?
- What are the key processes connected to the remediation options and what is their contribution to the impacts?

- How does a different time horizon affect the time-dependent impacts, and its potential significance for optimizing pollution causing processes?
- What are the strengths and weaknesses of LCA as a tool to assess the environmental sustainability aspects of site remediation?

1.3 Overview of the Thesis

This thesis is divided into eight chapters. After the first introductory chapter, a general framework of LCA, in four basic steps is described in chapter two. The methodology of this study is detailed in the third chapter. Results of LCIA, environmental interventions and contribution analysis are presented in the fourth chapter. A sensitivity analysis is performed in chapter five to evaluate the results further. It is followed by discussion of the implications of the results in chapter six. Chapter seven discusses the results from a sustainability perspective. The last chapter provides concluding remarks and summarizes the main findings.

CHAPTER 2

LIFE CYCLE ASSESSMENT – THE FRAMEWORK

LCA is a method of quantifying environmental impacts associated with a system where both inputs and outputs of the system connected with production, use, and disposal of the product or service activity are considered. The impacts are assessed along the entire life cycle that includes all the stages from extraction of raw materials, transportation and production to distribution, maintenance, use, recycling and final disposal (Consoli et al., 1993). The results from the assessment are characterized as environmental implications of the significant stages in the life cycle of products and services.

LCA is used as a decision support tool by many organizations. Its usefulness has been recognized historically as a tool to compare alternative products and technologies through quantitative evaluation of the environmental impacts. In recent years, use of LCA has increased considerably. Much is expected from this approach, but there is concern and criticism related to some features of the LCA results (Owen, 1997; Gloria et al., 2006; Perriman, 1995; Heijungs et al., 2004). While the basic framework is widely accepted, certain aspects such as impact-assessment and interpretation of results are still much debated subjects. Different LCA methods vary from each other in many respects, for example selected impact categories, coverage, characterization factors and data requirements. The variations can easily result in different interpretations of the results and affect decision making. Some studies have shown that inadequacy of underlying fate-exposure models for toxicity characterization, particularly in the case of metals, can lead to a possible overestimation of the impact (Owen, 1997; Heijungs et al., 2004).

The issue of time and space is another problem in LCA that has been the subject of much debate and research. LCIA results are presented on a broad scale that lacks temporal and spatial specificity. Past studies have shown that spatially derived characterization factors can differ substantially from generic factors, reflecting the importance of the spatial aspect in impact categories such as acidification and eutrophication potential (Potting et al., 1997; Huijbregts et al., 2000a). Also, it has been shown that ecotoxicity impact due to metals is dependent on ambient environmental conditions, thereby emphasizing the need for "spatially differentiated" modeling (Strandesen et al., 2007). While the lack of specificity may result in less precise results, it does enable a wide applicability of LCA as a decision tool.

In the use of LCA it is observed that cumulative impact of long term emissions can be much greater when evaluated with the same impact factors as current emissions (Ecoinvent, 2004). While this kind of assessment in the present LCIA methods is a concern, long term emissions cannot be ignored especially in case of waste management processes. Finnveden and Nielsen 1999, presented an argument in support of considering landfill emissions beyond 100 years (which is often a default standard timeframe in the use of LCA) by pointing to the fact that the utility of a landfill area is restricted far beyond 100 years and that only a small fraction of the total emissions are emitted during the first 100 year period. Long term emissions for disposal related processes are found to be particularly meaningful in LCA; however, their relevance in other processes may be limited (Doka, 2003).

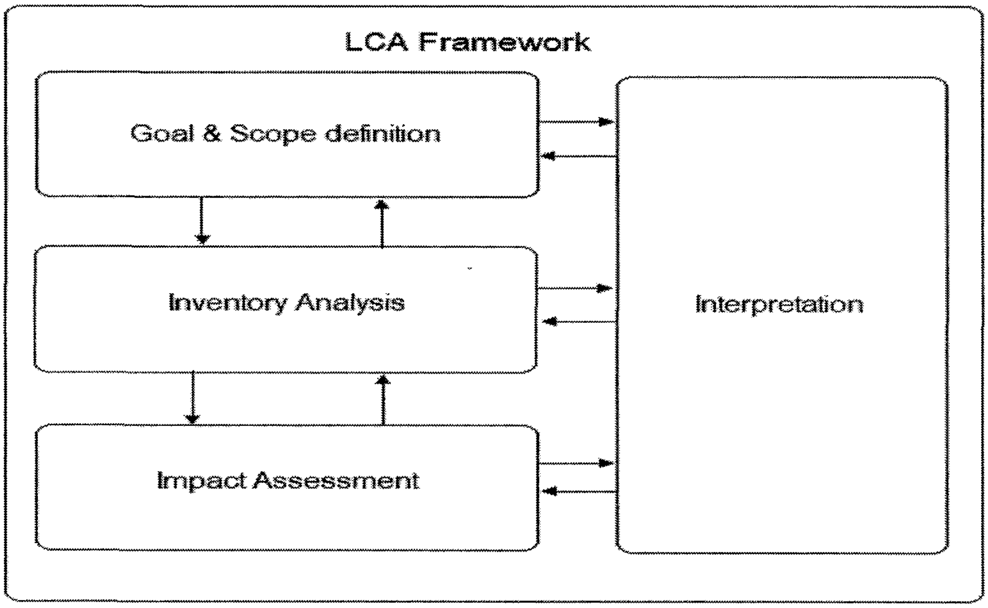
The use of discounting (differentiated weighting) has been suggested by some authors, where every additional year is assigned a lower weight (Hellweg et al., 2003).

But the discounting approach can be difficult to implement because it not only requires technical knowledge and assessment of future uncertainty; but also stirs ethical debates regarding the moral obligation to future generations and non-human entities (Heijungs et al., 2004).

The answer to the issue of time and space in LCA is not an easy one. While there is a general consensus about the procedural aspects of LCA, there are on-going efforts leading to modifications that aim to provide more temporal and spatial specificity. There are several available guidelines addressing the framework and terminology in LCA. For example, SETAC's (Society of Environmental Toxicology and Chemistry) "Code of Practice" (Consoli et al., 1993) and the ISO (International Organization for Standardization) series (14040, 1997; 14041, 1998; 14042, 2000a; 14043, 2000b). A Handbook on LCA, an "operational guide to ISO standards", has also been published to provide step by step guidance at each phase in LCA (Guinée et al., 2002)

The framework of LCA is has been outlined as consisting of four phases: goal and scope definition, inventory analysis, impact assessment and interpretation (ISO 14042 2000a; Guinée et al., 2002). The following sections give a brief overview of the LCA steps.

Figure 2.1 General Scheme for LCA (ISO 14040, 1997)



2.1 Goal and Scope Definition

This is the first step in the LCA where objectives of the study, the scope, the functional unit that will be used and the alternatives to be compared are described (ISO 14040, 1997; Guinée et al., 2002). It is important to describe the purpose for conducting LCA and the context in which the results will be used in order to assure that the results obtained are useful in accomplishing the objectives (ISO 14040, 1997). This phase provides the foundation for the study and guides the choices that will be made in the following phases.

Defining the functional unit is an important part of this step. The functional unit identifies the primary "function(s)" of a system based on which alternative systems are considered "functionally equivalent" (Guinée et al., 2002). This facilitates determination of reference flows for each option. Among other things, this means that the functional unit must have characteristics in common with all of the alternatives that will be compared. Functional unit therefore simply facilitates the comparison between two or more products or product systems. When alternative remediation technologies are compared for a particular site, it has been recommended to use the mass of contaminated soil as the functional unit (Shakweer and Nathanail, 2003). For sites with contaminated ground water or other classes of contamination, analogous choices could be made. The use of treated soil as the functional unit has been suggested by Diamond et al., 1999 but according to Shakweer and Nathanail, 2003 it would be an inappropriate unit of comparison as different technologies achieve different clean-up levels.

Additionally, the selected alternatives should be in accordance with the goal and scope of the study. The alternatives should also have an actual possibility of being used as substitutes (Guinée et al., 2002).

2.2 Inventory Analysis

Inventory analysis includes defining the system boundaries, allocation of resources for multifunctional processes, and quantifying the environmental interventions from the defined system with respect to the functional unit (Guinée et al., 2002). Description of the system boundaries includes specifying the sources of data for the selected processes, the choice of impact assessment method and limitations (Guinée et al., 2002). Limitations state the life cycle stages excluded from the system for the particular study, for example environmental interventions related to manufacturing of equipment and machinery. The selected processes are often depicted in the form of flow diagrams that create a simplified model of the system.

The inventory data represents the "cradle to grave" perspective of LCA as all the substances emitted and resources used during the life cycle of a product or a service are quantified (Guinée et al., 2002). However, this information is not sufficient for decision making because the environmental impacts of emissions are not assessed. The next phase, LCIA, processes the inventory data further and enables an interpretation in terms of impacts associated with various emissions (Saur et al., 1996).

2.3 Life Cycle Impact Assessment (LCIA)

The impact assessment has been divided into six phases: selection of impact categories, classification, characterization, normalization, grouping and weighing (Guinée et al., 2002; ISO 14042, 2000a). The selection of impact categories involves identifying categories according to the goal and scope of the study. In the next phase, classification, the inventory data is assigned to the selected impact categories. The characterization phase is the last mandatory step (ISO 14041, 2000a). A modeling approach is used to derive characterization factors, which are then used to convert the inventory data into impact category indicators (Guinée et al., 2002). These indicators represent the impact potential of each environmental intervention. Overall, characterization determines the potential contribution of the system to various environmental impacts.

Normalization is often performed as the next step. According to ISO standards, normalization is not a mandatory step, but it is often performed to obtain a more comprehensive view. Normalization relates the pollution and/or depletion created by a product to its surroundings (ISO 14042, 2000a). In other words, "normalization relates the micro world of an LCA study to the macro world in which the product/service is embedded" (Lindeijer, 1996). Normalization results are therefore spatially bounded by local, regional or global references. They are obtained by dividing the characterized magnitude of each impact category by its normalization factor (an estimated total impact in that category in a given reference area). This results in the unit-less measure of impacts. For example, normalized impact for global warming can be obtained by dividing the characterized global warming impact caused by a product or a system by the total global warming impact produced in a given area during a one year period.

The next optional step is grouping, where impact categories are aggregated into one or more groups based on characteristics such as spatial scale or type of environmental intervention (Guinée et al., 2002). No clear guidelines are available for this step.

Weighting is another optional step where normalized results are assigned weighting factors. These factors are based on value choices such as standards, "willingness to pay" and expert judgment (Guinée et at., 2002). Presently there are no recommended weighting factors or methods for performing this step. The ISO 14042 does not allow weighting in comparative studies.

2.4 Interpretation

Interpretation involves drawing final conclusions and recommendations with respect to the defined goal and scope of the study (Guinée et al., 2002).

CHAPTER 3

METHODOLOGY

3.1 Site Characteristics

A hypothetical site of area 625 yd^2, with a total contaminated soil of volume 5000yd^3 (approximately 5000 tons) is developed for this study. The contamination extends to a depth of 8m in the vadose zone. The contaminants of concern are assumed to be organic in nature: Total Petroleum Hydrocarbon (TPH) and Benzene, Toluene, Ethylbenzene and Xylene (BTEX). The concentration of TPH and BTEX is assumed to range from 1 - 5000 mg/kg in soil. The soil type is assumed to be medium sandy. For the purposes of this study, there is assumed to be no interaction of the contaminants with ground water.

3.2 Goal and Scope of Study

The goal of this study is to assess the secondary impacts of a set of five site remediation alternatives and to evaluate the results from the perspective of environmental sustainability. As a prerequisite to the analysis, the remediation options are assumed to be feasible.

The functional unit is defined as remediation of 5000 yd^3 of soil. The design of the treatment options is generic, and lacks parameters such as site characteristics, hydrology and efficiency of technology. Although they can become overriding factors in technology selection at a particular site, the scope of this work is limited to the assessment of secondary environmental impacts that arise due to material and energy use at the site; and their implication from a sustainability perspective.

The results are intended to be used further to identify potential "hot spots" in the life cycle of materials and services used and draw conclusions for improvement of remediation practice. Finally, the results are to be used to discuss the usefulness of LCA as a tool to achieve environmental sustainability goals.

A simplified hypothetical site was therefore developed and five possible remediation scenarios were selected to perform LCA. The remediation scenarios were selected to be illustrative of technical types and not necessarily as the techniques that would be selected for remediation of this particular type of site.

3.3 Treatment Scenarios

The following five treatment scenarios were selected. Table 3.1 presents a short description of each technology.

(1) Monitored Natural Attenuation (MNA)
(2) Bioremediation
(3) Chemical oxidation
(4) In-situ Solidification/Stabilization (S/S)
(5) Ex-situ Solidification/Stabilization (S/S)

For MNA, option (1), it is assumed that the contaminants will degrade in a period of 50 years, hence the monitoring time. Natural attenuation is a process of risk reduction at the site due to the natural course of biodegradation or chemical degradation, dilution, dispersion, volatilization and sorption (US EPA, 1999b; US EPA 2004). Application of natural attenuation as a remedial alternative needs careful evaluation of a number of site parameters such as hydrology, contaminant distribution, fate, geochemistry and receptor location (US EPA, 2004). Long-term monitoring is an integral part of a natural attenuation approach where the collected data is used for evaluation of contaminant behavior with time, efficiency of natural attenuation, and verification of the risk to down-gradient receptors (US EPA, 2004). The degradation rate is slow and can sometimes take a few hundred years to reach a regulatory standard. Therefore, the 50-year timeframe used in this study should be seen as only a working estimate of time.

Table 3.1 Treatment technology description

Treatment Technology	Description	
(1) MNA	Long-term monitoring	Monitoring time: 50 yrs 2 workers/month
(2)Bioventing	2 Vent wells (7m deep, dia. 6.25 cm) 6 Monitoring points (7 m deep, dia. 20 cm) Radius of Influence, 10 m Blower (500 W)	Tipper truck (20t) Treatment time: 4 years 10 workers/d: 1 month 2 workers/month: 47 months
(3) Chemical oxidation	50 Paired injection steel wells (6 and 2 m deep, dia. 6.25 cm) Radius of Influence, 2 m 4 monitoring wells (8 m deep, dia. 6.25 cm) Oxidizing agent: Fenton reagent	Pump (1kW) Tipper truck (20t) Treatment time: 1 year 10 workers/d
(4) In-situ S/S	Auger – Caisson system Excavator Compactor	Tipper truck (40 t) Treatment time: 5 months 8 workers/d
(5) Ex-situ S/S	Mixer (Pug mill) Excavator Compactor Front loader	Hopper & blower Tipper truck (40 t) Treatment time: 5 months 10 workers/d

The design for bioventing (option 2), is based on the EPA guidance manual, Bioventing Principles and Practice (US EPA, 1995b). Estimation of number of vent wells and monitoring points is based on the guidelines provided by the manual. An average biodegradation rate (K_B) of 3.29 mg/kg/day from an average of 145 sites (Afcfee, 1996) was used to estimate the treatment time for bioventing.

Bioventing is a process of injecting air into contaminated soil to aerate the soil and achieve biological degradation of hydrocarbons or other biodegradable materials. Air at a low rate is pumped into the soil to facilitate biodegradation while avoiding volatilization of the hydrocarbon contaminant. Where applicable, bioventing can bring about significant degradation and reduction in the level of contamination (US EPA 1995a), although it is a time consuming treatment technology that frequently takes a number of years to achieve the contamination reduction standards.

Option (3), chemical oxidation involves oxidation of BTEX and TPH by using Fenton reagent (hydrogen peroxide and ferrous sulfate) as an oxidizing agent. The required Fenton reagent to oxidize the hydrocarbon was estimated from available reports on actual site applications (ITRC, 2005; US EPA, 1998). The injections were assumed to be performed intermittently during the course of one year.

Chemical oxidation has been used as an in-situ technology to destroy hydrocarbon contamination. The treatment time is usually a few months (US EPA, 1998). Hydrogen peroxide is one of the frequently used oxidizing agents among others such as $KMnO_4$ and Ozone (ITRC, 2005). Once injected into the contaminated zone, peroxide disintegrates into oxygen and water within hours. The chemical reaction generated by this solution, originally described by Fenton, 1894, creates a hydroxyl radical that very effectively oxidizes complex organic compounds. Typically, peroxide is used at remediation sites in liquid form at dose concentrations that range from five percent to fifty percent by weight.

Remediation option (4), in-situ (S/S), involves use of cement and bentonite as binders to solidify and stabilize the contaminated soil. On-site mixing machinery – auger/caisson system was assumed to be used. Option (5) was designed for ex-situ (S/S) treatment where contaminated soil was excavated, blended in a pug-mill and disposed of off-site, which required transportation. The amount of binders required for the treatment was estimated from available reports on actual site applications. The transportation distances for suppliers, landfill and clean-fill source were assumed to be 75 km. An average time of operation, 5 months (US EPA, 2000) was assumed for both in-situ and ex-situ treatment.

3.4 Life Cycle Inventory (LCI)

The system boundary for generating the LCI included the remediation processes occurring at the site and the transportation to and from the site. Figure 3.1 presents a schematic representation of the processes considered for the five treatment options studied. Three main life cycle stages were included for options (2), (3), (4) & (5), viz., site preparation, treatment and site dismantling. Transportation of material and equipment was included in the site preparation stage; material and electricity was used during the treatment stage and finally transportation was considered again during site dismantling to return the equipment to its original location. For option (1) only transportation for monitoring was considered.

Secondary data for this analysis was obtained from the Ecoinvent and Franklin US databases provided with the SimaPro 7.0 software (PR'e Consultants, 2006). The life cycle processes included in the Ecoinvent database (Ecoinvent 1.3, 2000) and the Franklin US databases (Franklin Associates, 1998) were considered as the system boundary for the material and energy input. The CML 2 baseline (2000) method was chosen for performing the LCIA (Guinée et al., 2002)

The calculated amount of materials and energy used for these processes is presented in Table 3.2. The environmental load for each option is presented in relation to the functional unit. The required diesel and electricity for equipment operations were calculated according to the treatment time for each technology.

Table 3.2 Mass of material input

Material Input	MNA	Bioventing	Chemical oxidation	In-situ S/S	Ex-situ S/S
Portland cement (Kg)	-	-	-	$1x10^6$	$1x10^6$
Bentonite (Kg)	-	600	530	$4x\ 10^5$	$4x\ 10^5$
Sand (Kg)	-	1100	113	-	-
PVC (Kg)	-	16	-	-	-
Steel (Kg)	-	-	3400	-	-
Cement mortar (Kg)	-	150	1600	-	-
H_2O_2 (50%) (l)	-	-	10, 000	-	-
Iron(II)Sulfate(Kg)	-	-	20, 000	-	-
Electricity (KWh)	-	17520	100	-	9000
Diesel $_{\text{machinery}}$ (l)	-	-	-	38,000	57,000
Transport $_{\text{passenger car}}$ (Km)	72,000	30,000	16,000	48,000	60,000
Transport $_{\text{truck}}$ (Km)	-	300	450	5,550	53,000

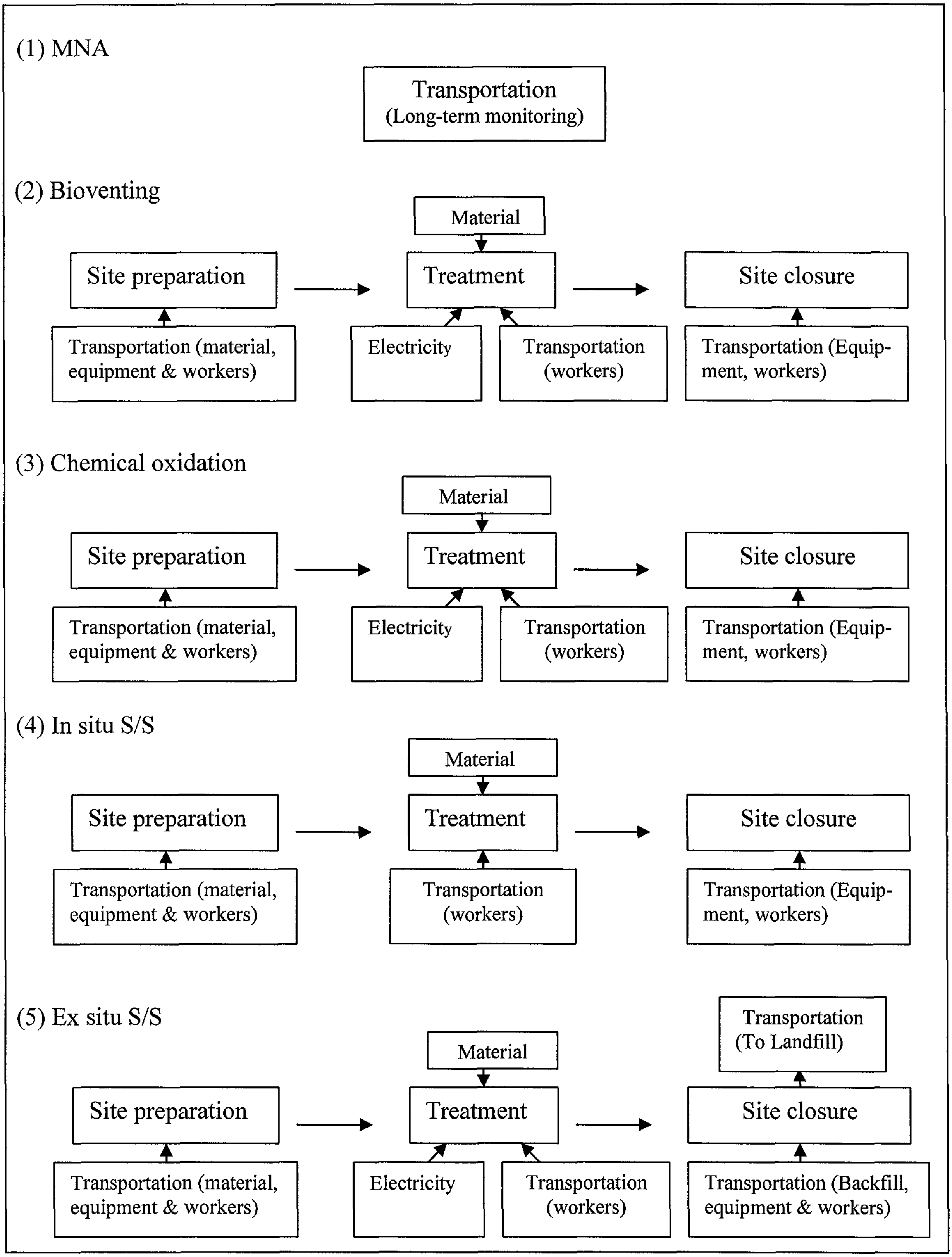


Figure 3.1 Processes forming the system boundary

The outcome of the LCI is the list of all resources used and substances emitted. The complete LCI data for the five remediation options is provided in the appendix A. The assumptions and limitations used in LCI generation for this study are the following:

- The site characterization phase of remediation was not included.
- The transportation distance from the landfill and suppliers was assumed to be 75 km. For personal transportation of workers, the distance from home to work-site was assumed to be 30 km.
- Resource utilization and emissions during manufacture of trucks, cars and equipment were not included in the LCI.
- All staff activities except transportation of workers (to and from the site) were excluded in the LCI.
- Time, energy and material inputs were estimated by considering a reduction in contaminant concentration of approximately 90-95% for each remediation option.
- Emissions from stabilized soil were not considered.
- Direct fugitive emissions from on-site contaminants during remediation were not considered.
- Contaminants were assumed to reach an asymptotic level in a period of 50 years for the MNA option.

3.5 LCIA Method

The standard method of CML - 2 (2000) was selected for impact assessment. It is a problem-oriented (mid-point) approach based on best available practice. The SimaPro 7.0 (PR′e Consultants, 2006) computational software tool was used to perform the impact assessment. The normalization step for characterized impacts was performed for this analysis.

The impact assessment method covers a set of core baseline impact categories – Abiotic Depletion Potential (ADP), Global Warming Potential (GWP), Human Toxicity Potential (HTP), Freshwater Aquatic Ecotoxicity Potential (FAETP), Marine Aquatic Ecotoxicity Potential (MAETP), Terrestrial Ecotoxicity Potential (TETP), Photochemical Oxidation Potential (PCOP), Acidification Potential (AP) and Eutrophication Potential (EP).

This impact assessment method elaborates a problem oriented approach that is based on the mid-point of the cause-effect chain of an environmental problem, rather than the end point of this chain (Guinée et al., 2002). Characterization factors for time dependent impact categories are based on fate-exposure models. Baseline characterization factors for GWP consider a 100 year time horizon, which is derived from the IPCC (Intergovernmental Panel on Climate Change) model for GWP. The ODP baseline factors are steady-state factors, developed by WMO (World Meteorological Organization). Characterization factors for toxicity are derived from a multimedia fate-exposure model, USES – LCA developed by Huijbregts et al., 2000b. The model uses a steady-state equilibrium that is based on an infinite time-horizon. Acidification potentials are also derived from steady-state models (Huijbregts et al., 2000a). In the case of Eutrophication however, the current characterization factors are not based on fate-exposure modeling (Guinée et al., 2002).

The CML method includes continental and global spatial scales for normalization. The global scale was chosen for this study in order to reduce geographical specificity.

CHAPTER 4

RESULTS

4.1 LCIA

The secondary impacts of the five remediation options were assessed by performing LCIA, including the normalization step. A category-wise comparison of the four options showed Natural attenuation to be the lowest impact option followed by Bioventing. The highest secondary impacts were produced by Ex-situ S/S. The relative magnitude of other impacts, particularly in the case of the bioventing and chemical oxidation options appeared to be diminished due to the pronounced impact of marine ecotoxicity. The LCIA results are presented in figure 4.1 – 4.5.

Results show that MAETP impact category had the highest contribution in the cases of bioventing, chemical oxidation and in-situ S/S. It was also an important category for ex-situ S/S. ADP was particularly significant for both of the S/S options due to a greater input of resources. GWP, AP, PCOP and EU were also significant for these two options. For MNA, direct emissions from transportation are considered. They produced a relative dominance of ADP and GWP followed by PCOP, AP and EP. No toxicity (HTP, FAETP, MAETP, and TETP) impacts were observed for this option.

For bioventing a high proportion of the total impact came from the electricity use (64.5%) to power the blower, passenger car (18%) for monitoring and bentonite for construction (13%). In the case of chemical oxidation, the use of H_2O_2 for oxidation was the most dominant process, contributing nearly 40% of the total impacts. The input of other materials such as steel and iron sulfate contributed 35.8 % and 6% respectively. Transportation of workers contributed 9% to the total impact. The use of Portland cement had the highest impacts in the case of in-situ S/S (55%). The use of diesel for onsite equipment operation contributed 13.5% and transportation by truck contributed 21%. In the case of ex-situ S/S, truck transportation had the highest contribution of 66% due to the transportation of stabilized soil to a disposal facility and bringing clean fill to the site. Portland cement contributed nearly 28% while diesel equipment operation contributed 3% to the total impacts.

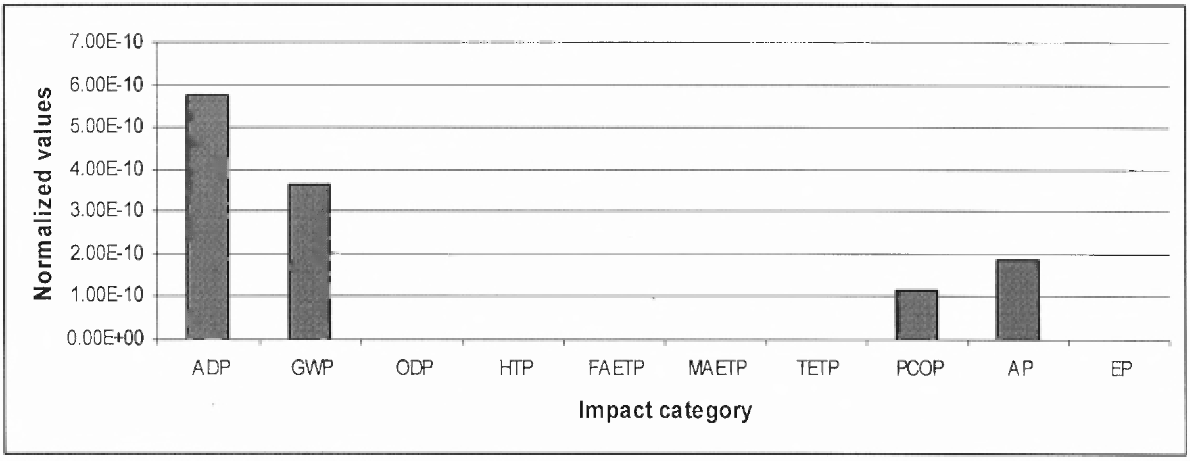


Figure 4.1 Option (1) MNA - Normalized impacts

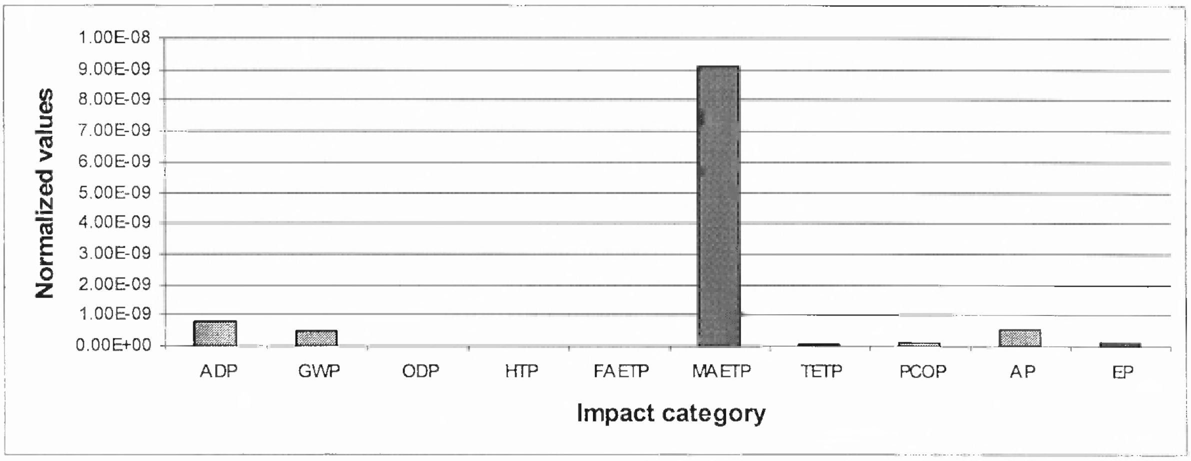


Figure 4.2 Option (2) Bioventing - Normalized impacts

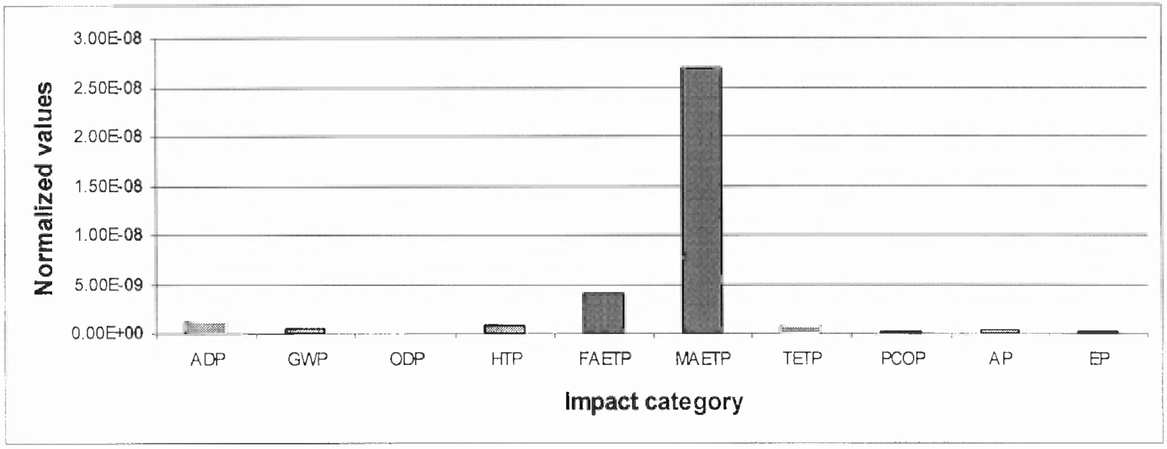


Figure 4.3 Option (3) Chemical oxidation - Normalized impacts

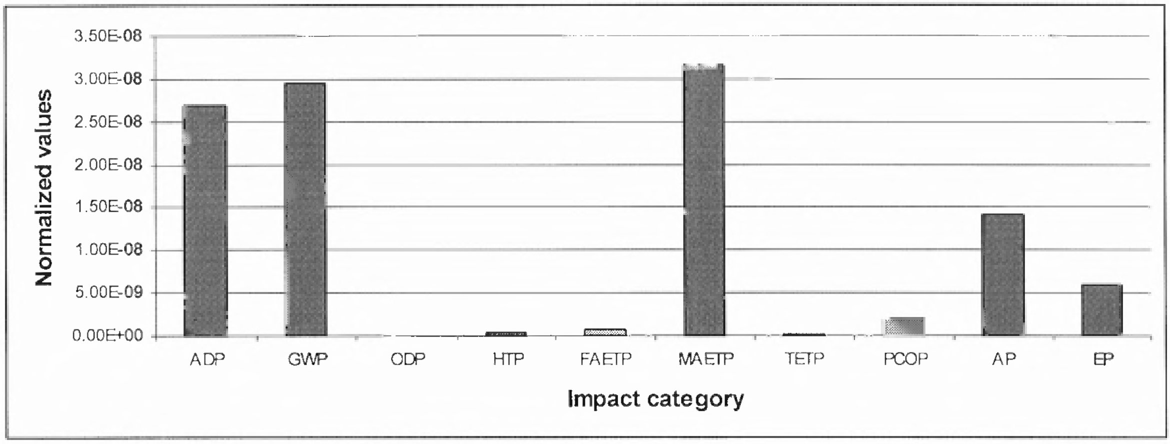


Figure 4.4 Option (4) In-situ S/S - Normalized impacts

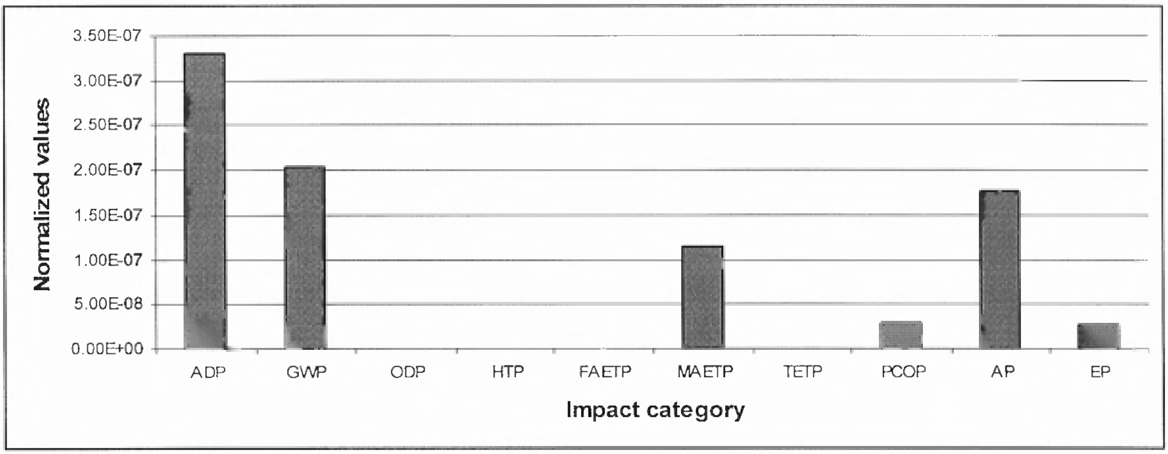


Figure 4.5 Option (5) Chemical oxidation - Normalized impacts

4.2 Depletion and Emissions

Table 4.1 presents the inventory of resource inputs and emissions for the five remediation options. These are normalized results. Substances contributing more than 1% of the total impact are presented here. The inventory is differentiated for each impact category and the compartment of release.

The ADP category was dominated by non-renewable resources such as coal, natural gas and oil in all the remediation options. In the case of global warming impact, carbon dioxide and methane emissions were the primary contributors.

The toxicity impact was found to be due mainly to metal emissions in the four remediation options, (2), (3), (4) and (5). For the HTP category, certain persistent hydrocarbon emissions such as benzene and polyaromatic hydrocarbons (PAH) were observed in addition to metals. In case of ex-situ S/S, particulate matter (PM), oxides of nitrogen and sulfur also contributed to HTP. FAETP showed emissions of metals such as copper, nickel, vanadium, barium and cobalt. In the case of the MAETP category, hydrogen fluoride emissions into the air compartment were found to be particularly dominant for all the treatment options except MNA. Metals were also found to be the main emissions in the case of TETP.

In the PCOP category, emissions of air pollutants such as oxides of sulfur and carbon monoxide were the main contributors for all options. The AP was dominated by oxides of nitrogen and sulfur in all the options. Finally, in the EP category oxides of nitrogen, ammonia and phosphorous were observed.

Table 4.1 Inventory of environmental interventions (Normalized values)

Substance by Impact-Category	Compartment	MNA	Bioventing	Chemical Oxidation	In-situ S/S	Ex-situ S/S
ADP						
Coal	Raw	-	3.94E-10	2.88E-10	4.58E-09	8.14E-09
Gas	Raw	3.19E-11	1.45E-10	3.90E-10	1.83E-09	2.28E-08
Oil	Raw	5.43E-10	2.67E-10	1.55E-10	2.03E-08	2.93E-07
GWP						
Carbon dioxide	Air	3.64E-10	4.37E-10	4.41E-10	2.96E-08	2.03E-07
Methane	Air	-	1.41E-11	1.36E-11	3.66E-10	-
ODP						
Halon 1211	Air	-	4.37E-15	1.18E-12	1.20E-12	1.20E-12
Halon1301	Air	-	6.60E-15	1.72E-12	4.38E-11	4.38E-11
HTP						
Antimony	Water	-	2.91E-13	-	-	-
Arsenic	Air	-	3.39E-12	1.05E-11	1.14E-10	2.52E-10
Barite	Water	-	-	-	2.66E-11	-
Barium	Water	-	-	-	2.20E-11	-
Benzene	Air	-	3.33E-13	-	5.21E-11	5.23E-11
Benzene	Water	-	4.61E-13	-	-	-
Beryllium	Air	-	2.47E-13	-	1.12E-11	-
Cadmium	Air	-	3.11E-13	-	2.87E-11	1.15E-10
Chromium VI	Air	-	5.12E-13	1.38E-10	1.34E-10	1.34E-10
Dioxins	Air	-		-	2.99E-11	-
Hydrogen fluoride	Air	-	5.36E-12	-	1.36E-11	6.35E-11
Nickel	Air	-	1.27E-12	1.01E-11	4.40E-11	3.40E-10
Nitrogen oxides	Air	2.18E-12	1.83E-12	-	1.23E-10	1.44E-09
PAH	Air	-	2.34E-13	2.76E-11	1.39E-10	1.39E-10
PAH	Water	-	-	1.78E-11	4.69E-11	4.69E-11
PM, < 10 um	Air	-	-	-	-	1.28E-10
Selenium	Air	-	9.02E-13	-	-	-
Sodium dichromate	Air	-	-	5.67E-10	-	-
Sulfur oxides	Air	-	-	-	-	3.12E-11
Thallium	Air	-	-	-	8.89E-11	8.89E-11

Substance by Impact-Category	Compartment	MNA	Bioventing	Chemical Oxidation	In-situ S/S	Ex-situ S/S
FAETP						
Barium	Water	-	3.50E-13	3.44E-11	1.89E-10	1.89E-10
Beryllium	Air	-	5.38E-13	-	2.35E-11	3.69E-11
Beryllium	Water	-	5.78E-13	2.28E-11	6.51E-11	6.51E-11
Cadmium, ion	Water	-	1.45E-12	-	-	2.98E-10
Cobalt	Water	-	8.46E-13	1.42E-10	1.68E-10	1.68E-10
Copper, ion	Water	-	2.88E-12	6.10E-10	2.03E-10	2.03E-10
Formaldehyde	Air	-	-	-	1.29E-10	1.93E-10
Hydrogen fluoride	Air	-	2.52E-13	-	-	-
Nickel	Air	-	6.59E-13	-	-	1.71E-10
Nickel, ion	Water	-	4.04E-12	1.58E-9	7.83E-10	7.83E-10
Selenium	Air	-	2.99E-13	-	-	-
Phenol	Water	-	-	-	-	3.57E-11
Vanadium	Air	-	2.68E-13	4.06E-11	6.85E-11	6.85E-11
Vanadium, ion	Water	-	2.76E-12	3.68E-10	4.18E-10	4.18E-10
Zinc, ion	Water	-	2.37E-13	2.16E-11	2.74E-11	3.57E-11
PAH	Water	-		2.30E-11	1.26E-10	1.26E-10
MAETP						
Barite	Water	-	-	7.63E-10	4.01E-09	4.01E-09
Barium	Water	-	-	5.26E-10	3.25E-09	3.25E-09
Beryllium	Air	-	-	-	2.57E-09	4.04E-09
Beryllium	Water	-	-	5.37E-10	1.53E-09	1.53E-09
Cobalt	Water	-	-	7.27E-10	8.59E-10	-
Copper, ion	Water	-	-	4.88E-10	-	-
Hydrogen fluoride	Air	-	6.05E-09	1.16E-08	2.17E-08	1.01E-07
Nickel	Air	-	-	-	5.27E-10	4.07E-09
Nickel, ion	Water	-	-	4.09E-09	2.17E-09	2.17E-09
Thallium	Air	-	-	-	5.87E-10	-
Selenium	Water	-	-	3.08E-10	-	-
Vanadium	Air	-	-	1.14E-09	1.92E-09	1.92E-09
Vanadium, ion	Water	-	-	1.40E-09	1.60E-09	1.60E-09
TETP						
Arsenic	Air	-	3.55E-12	1.03E-11	1.12E-10	2.48E-10
Chromium VI	Air	-	-	1.24E-11	-	-
Chromium VI	Soil	-	9.26E-13	3.66E-11	4.85E-10	4.85E-10
Formaldehyde	Air	-	-	-	1.12E-10	1.67E-10

Substance by Impact-Category	Compartment	MNA	Bioventing	Chemical Oxidation	In-situ S/S	Ex-situ S/S
Nickel	Air	-	9.53E-13	7.14E-12	-	2.40E-10
Mercury	Air	-	4.44E-11	1.45E-10	3.41E-09	4.21E-09
Sodium dichromate	Air	-	-	1.06E-10	-	-
Vanadium	Air	-	8.09E-13	1.18E-10	2.00E-10	2.00E-10
PCOP						
Carbon monoxide	Air	1.14E-10	4.68E-11	2.57E-11	1.01E-09	1.80E-08
Ethane	Air	-	-	5.71E-13	-	-
Formaldehyde	Air	-	-	-	1.72E-11	-
Methane	Air	-	1.55E-12	1.53E-12	4.11E-11	-
Pentane	Air	-	-	6.97E-13	-	-
Sulfur dioxide	Air	3.27E-12	4.68E-11	1.53E-11	2.21E-10	9.26E-09
Sulfur oxides	Air	-	-	1.01E-11	4.54E-10	-
			-	-	-	-
AP						
Ammonia	Air	-	-	-	1.46E-10	-
Nitrogen oxides	Air	1.61E-10	1.41E-10	7.26E-11	9.09E-09	1.06E-07
Sulfur dioxide	Air	2.44E-11	3.77E-10	1.90E-10	1.66E-09	6.92E-08
Sulfur oxides	Air	-	-	-	3.40E-09	-
EP						
Ammonia	Air	-	-	1.07E-12	7.74E-11	6.73E-08
COD	Water	-	-	8.63E-12	-	-
Nitrate	Water	-	-	1.73E-12	-	-
Nitrogen oxides	Air	1.02E-10	8.93E-11	4.59E-11	5.74E-09	-
Phosphorus	Water	-	9.49E-13	7.97E-12	-	-

4.3 Contribution Analysis

Contribution analysis, also referred to as “dominance analysis” helps in identification of constituent processes in impact assessment results. Knowledge of the share of certain processes that contribute to an impact category can help identify the source of emissions.

This analysis can be helpful in developing pollution prevention or reduction strategies by redesigning products (Heijungs & Kleijn, 2005). Appendix B present results of contribution analysis for the remediation options. Processes contributing to more than 1% of the overall impact were considered.

A category-wise analysis for each option showed dominance of energy based processes such as use of coal for boilers; natural gas and crude oil in the ADP category. This was due to the energy dependence of on-site activities such as use of electricity and diesel for transportation. Also, the production and processing of materials such as cement is an energy intensive process that further leads to dominance of non-renewable sources of energy in the ADP category. ADP was a significant impact category for option (4) and (5) because of greater material input than in the other options. For MNA (option 1), ADP was due to the gasoline consumption for transportation.

Global warming gases (CO_2 and methane) for bioventing and chemical oxidation came from transportation of workers, and the use of fuel oil burned in industrial furnaces and coal in boilers for electricity production. For the S/S options (both in-situ and ex-situ), onsite equipment use and transportation related activities were important contributors to GWP. Clinker production was also a significant contributor due to the energy intensive nature of cement production. The processes causing ODP varied from chlorine gas production to industrial use of coal and fuel oil.

HTP, in the case of bioventing was mainly due to burning of coal for electricity generation. In the chemical oxidation option, HTP was mostly impacted by processes related to steel and H_2O_2 production. For S/S (in-situ) processes related to clinker production had a significant impact on HTP. Direct emissions from the truck operation, clinker production and the production of fuel oil for transportation were the main processes causing HTP in case of ex-situ S/S.

The FAETP category was mainly impacted by waste management activities such as disposal in a landfill. For MAETP, hydrogen fluoride emissions (air compartment) due to burning of coal in industrial processes stood out as the most dominant emission in case of bioventing. For other options, disposal processes along with use of coal were significant.

Processes causing terrestrial ecotoxicity were more varied for the four treatment options, ranging from burning of coal in power production in the case of bioventing to production of steel in the case of chemical oxidation, and clinker production for the S/S scenarios.

Transportation related activities had a high share of contribution to the following categories: GWP, PCOP, AP and EP. This was due to the emissions of carbon dioxide, oxides of sulfur and nitrogen from vehicular operation. PCOP, AP and EP were also impacted by the industrial use of non-renewable resources.

This analysis considered the significant processes (contributing more than 1%) leading to emissions into the air, water and soil compartments. In addition to the use of energy in processing activities and directly in electricity use and transportation, disposal related processes were identified to be important contributors.

CHAPTER 5

SENSITIVITY ANALYSIS

5.1 Background

Characterization factors are often based on steady-state modeling where an infinite time horizon is chosen to determine impact potential (Guinée et al., 2002; Hertwich et al., 1998; Huijbregts et al., 2000). This ensures that long term impacts of emissions are captured and the new level of concentration represents a steady-state in the dose-response relationship.

Previous work has shown that choice of time horizon can be an important factor in determining the magnitude of an impact (Huijbregts et al., 2001; Zelm et al., 2007; Solomon and Albritton, 1992). Huijbregts et al., 2001 performed a scenario analysis for toxicity potentials of 181 substances by using different time horizons. In a comparison of toxicity potentials for 20, 100 and 500 years with toxicity potential for an infinite time horizon, it was found that for metals the time dependent difference can be of several orders of magnitude (6.5) and that a large part of the impacts is passed on to the future generations.

Zelm et al., 2007 used an end-point impact assessment approach to develop characterization factors for acidification potential in different time horizons (20, 100 and 500 years). Characterization factors were found to approach a steady-state after a period of only 500 years. An increase in characterization factors with time was observed because of the decreasing buffering capacity of soil. Another study by Solomon and Albritton, 1992, developed time-dependent ozone depletion factors to determine the change in magnitude of ozone depleting substances with time. While a steady-state was reached within 500 years for all substances, it was found that the magnitude of some substances like bromotrifluoromethane - Halon 1301 and carbon tetrachloride (CCl_4) remains almost the same in different time horizons, other substances that have a shorter life time (for example, Halon 2402, Halon 1211 and HCFCs) tend to have a much higher ODP over a smaller time period.

Applying available dynamic models to a set of environmental concerns can provide important insight to interpretation of LCIA results. A sensitivity analysis was therefore performed to examine the impacts from site remediation with respect to different time horizons (20, 100 and 500 years). Alternative characterization factors developed for the problem oriented (mid-point) approach were used (Guinée et al., 2002). The impact categories that are known to have time-dependent impacts are: GWP, ODP, HTP, FAETP, MAETP, TETP, AP and EP.

In the case of GWP, steady-state characterization factors have not been developed (Guinée et al., 2002) therefore the sensitivity analysis uses 20 and 500 year time horizons as the alternatives. Also, the mid-point based time dependent AP and EP characterization factors are not available. This study did not include them in the sensitivity analysis. However, since the AP characterization factors for 500 year time horizon were found comparable to the steady state factors developed by Huijbregts et al., 2000a in a study by Zelm et al., 2007, it can be assumed that the AP category in the following results represents a 500 year time horizon.

5.2 Results of Sensitivity Analysis

The results of the analysis are presented for each remediation option (Figure 5.1 – 5.17). Impact assessment with the baseline characterization is also presented along with the alternative characterization for a comparative view.

In the case of MNA, no change was observed with a different time horizon. This can be attributed to the negligible impact in the toxicity categories. The GWP was only due to carbon dioxide emissions, whose impact potential does not differ in the three time horizons (20, 100 and 500 years) (Guinée et al., 2002).

Characterization in three different time horizons shows a decrease in GWP as the time horizon lengthens. The results depict an average decrease of 86% from the 20 year time horizon to the 500 year horizon in options (2), (3), (4) and (5). Global warming was caused primarily by two major emissions: methane and carbon dioxide. The decrease in GWP impact is due to the gradual removal of global warming gases through various mechanisms. However, the decrease observed in the results is only due to the decrease in methane levels, as the characterization factor for carbon dioxide does not vary in the three time horizons (20, 100 and 500 years).

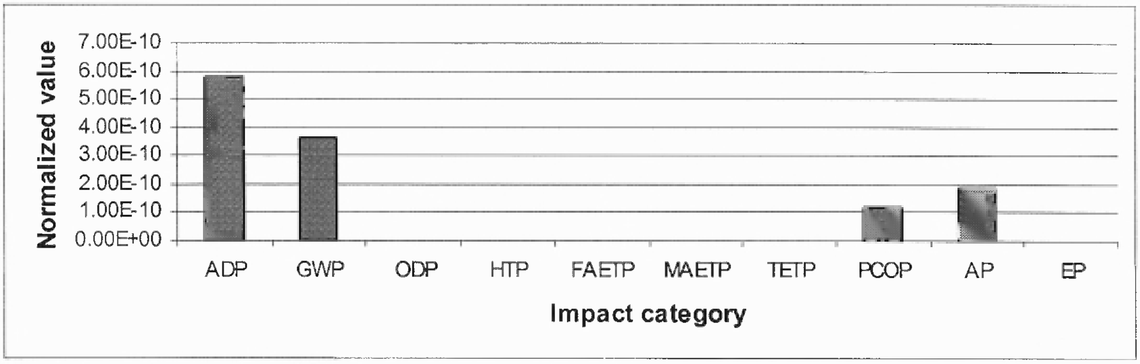


Figure 5.1 Option (1) MNA - Normalized impact (Baseline characterization)

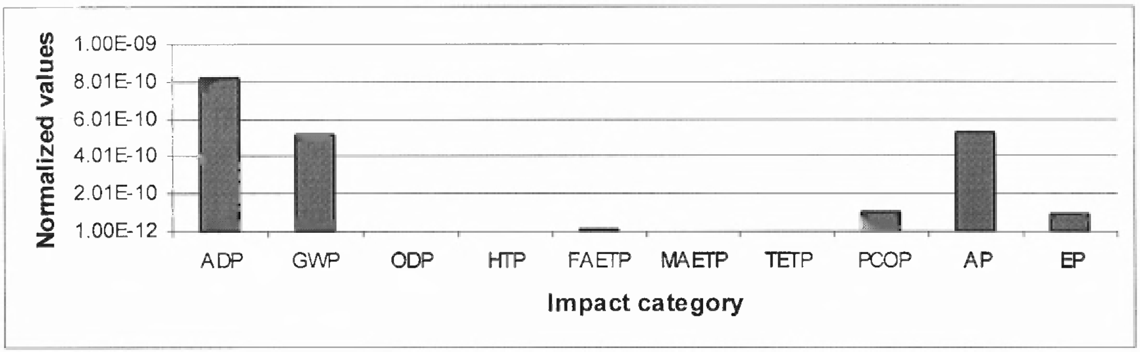


Figure 5.2 Option (2) Bioventing - Normalized impacts (20 year Time horizon)

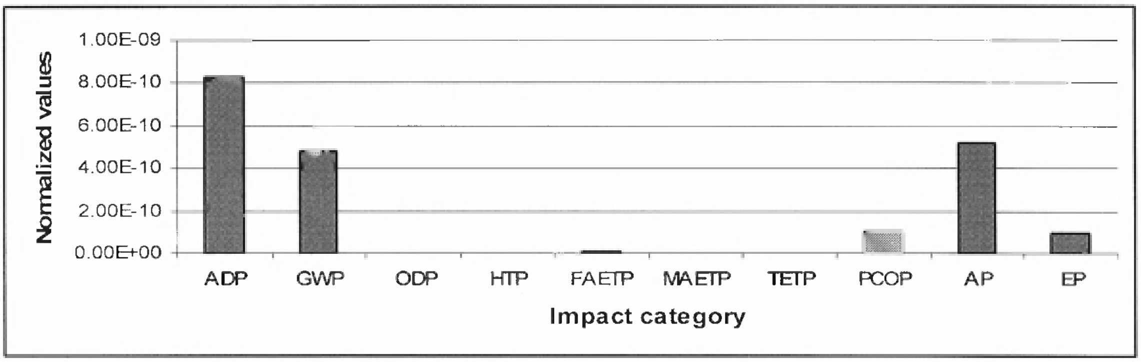


Figure5.3 Option (2) Bioventing - Normalized impacts (100 year Time horizon)

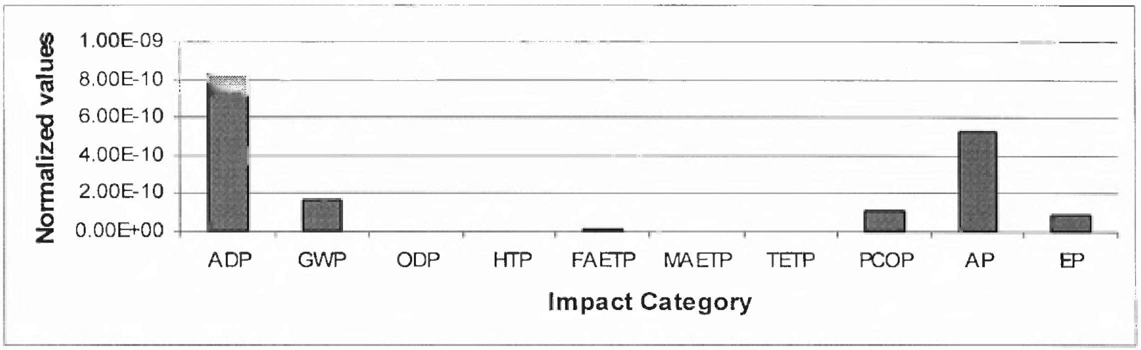


Figure 5.4 Option (2) Bioventing - Normalized impacts (500 year Time horizon)

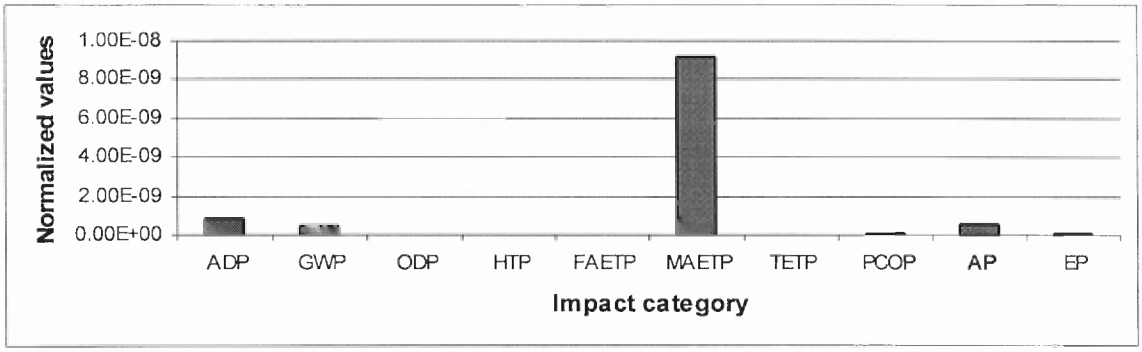


Figure 5.5 Option (2) Bioventing - Normalized impacts (Baseline characterization)

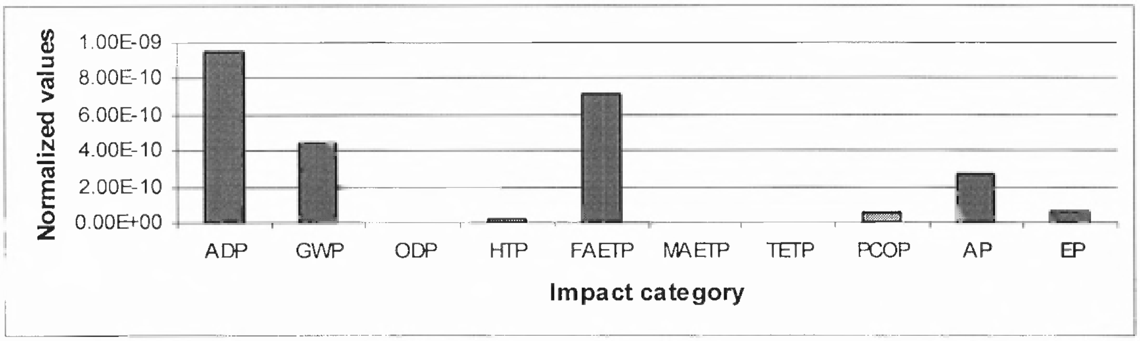


Figure 5.6 Option (3) Chemical oxidation - Normalized impacts (20 year Time horizon)

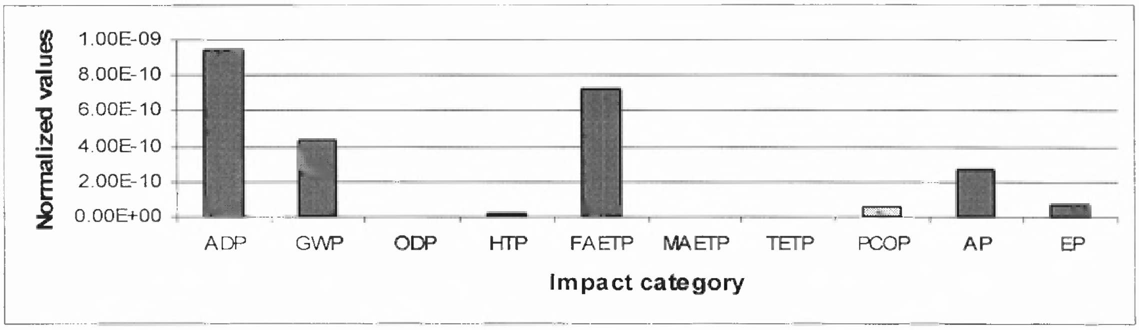


Figure 5.7 Option (3) Chemical oxidation - Normalized impacts (100 year Time horizon)

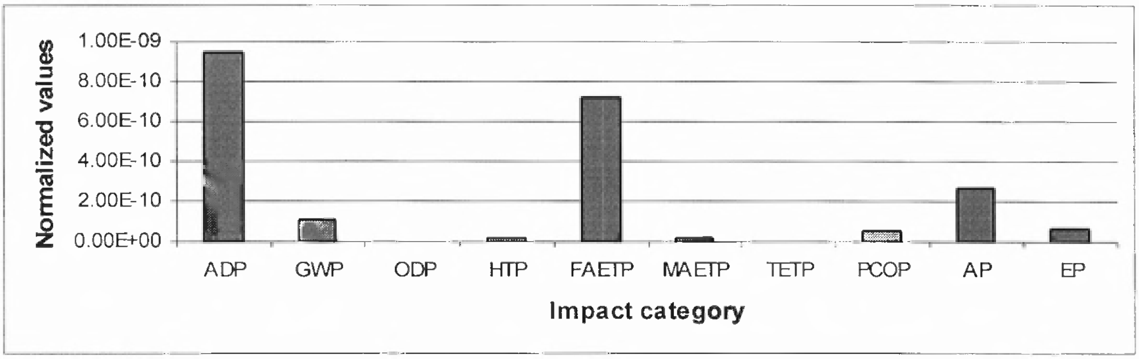


Figure 5.8 Option (3) Chemical oxidation - Normalized impacts (500 year Time horizon)

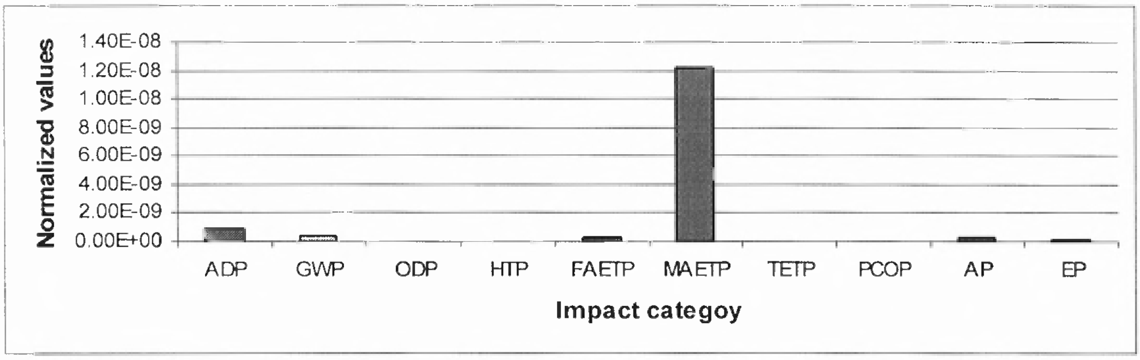


Figure 5.9 Option (3) Chemical oxidation - Normalized impacts (Baseline characterization)

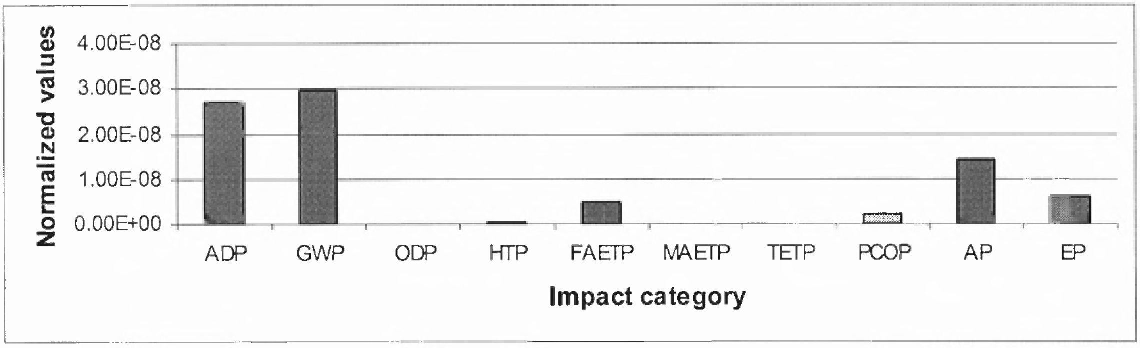


Figure 5.10 Option (4) In-situ S/S - Normalized impacts (20 year Time horizon)

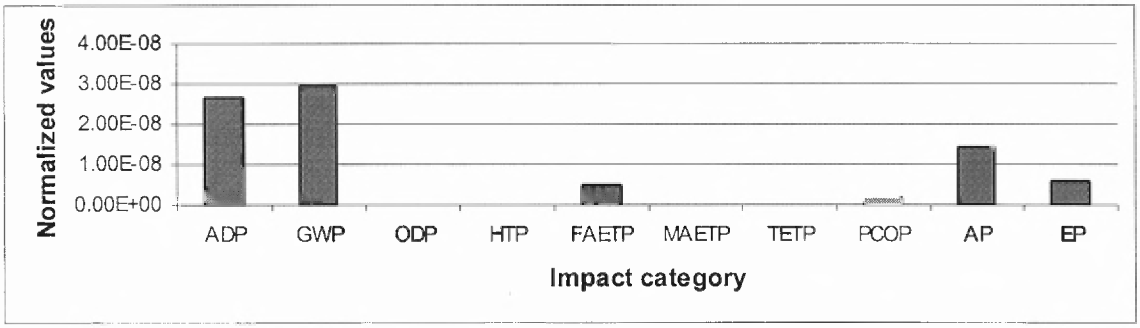


Figure 5.11 Option (4) In-situ S/S - Normalized impacts (100 year Time horizon)

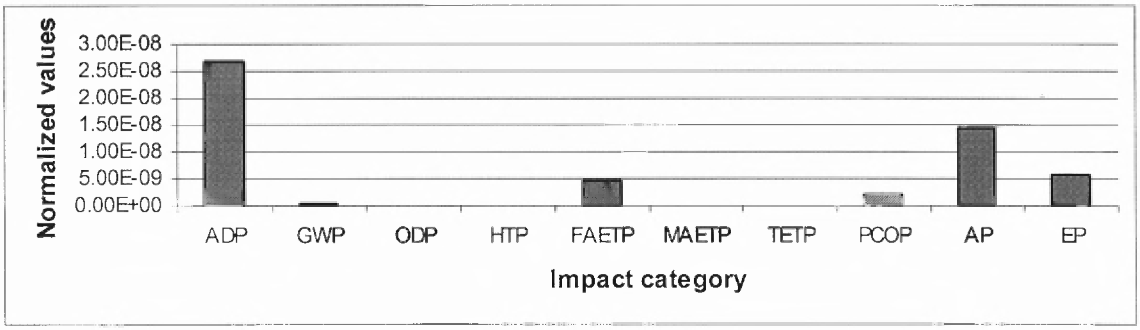


Figure 5.12 Option (4) In-situ S/S - Normalized impacts (500 year Time horizon)

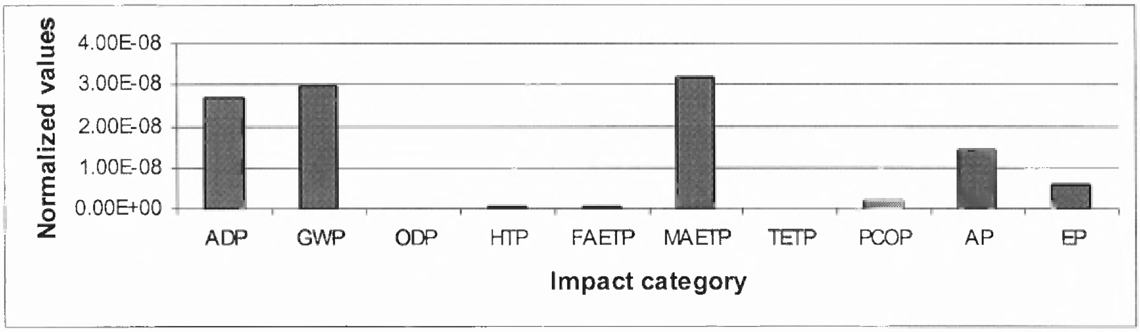


Figure 5.13 Option (4) In-situ S/S - Normalized impacts (Baseline characterization)

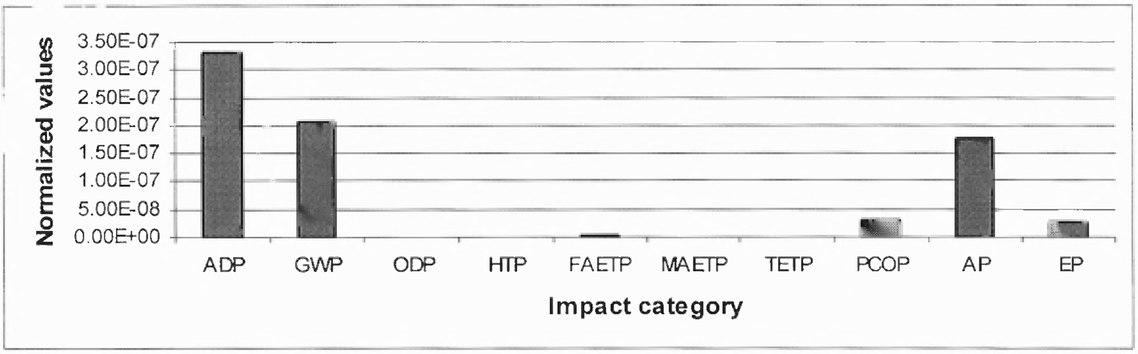


Figure 5.14 Option (5) Ex-situ S/S - Normalized impacts (20 year Time horizon)

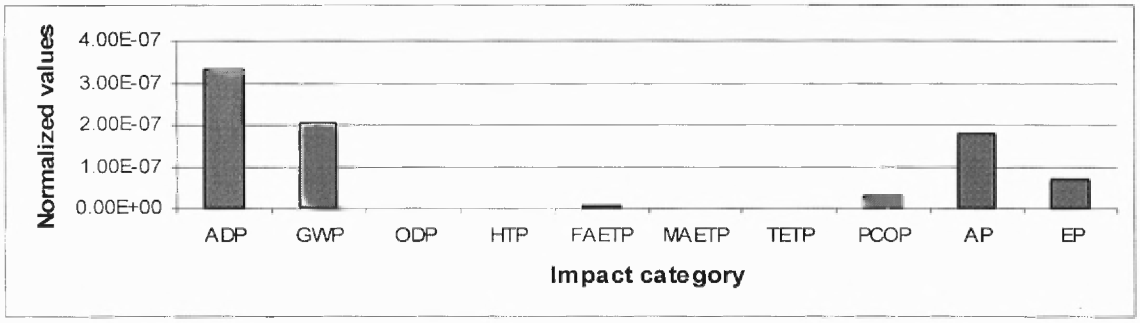


Figure 5.15 Option (5) Ex-situ S/S - Normalized impacts (100 year Time horizon)

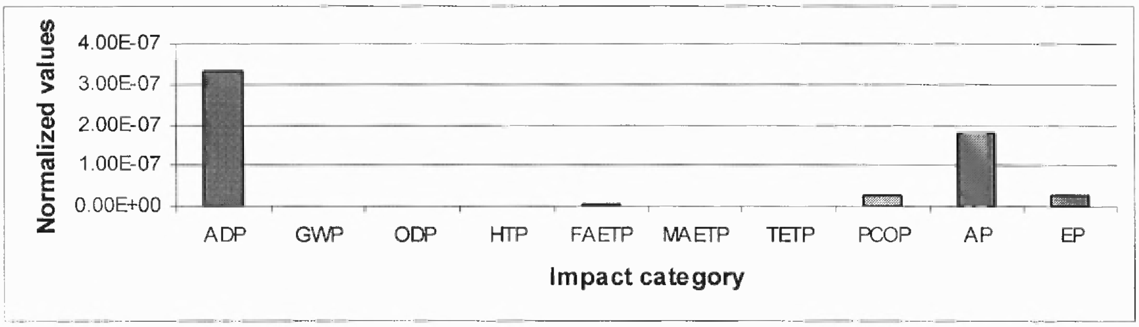


Figure 5.16 Option (5) Ex-situ S/S - Normalized impacts (500 year Time horizon)

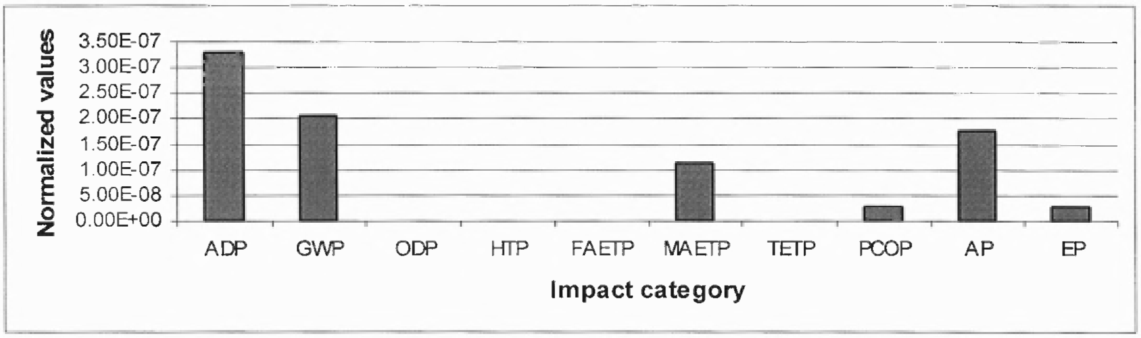


Figure 5.17 Option (5) Ex-situ S/S - Normalized impacts (Baseline characterization)

ODP was caused primarily by bromochlorodifluoromethane - Halon 1211 and bromotrifluoromethane - Halon 1301. The results of the sensitivity analysis do not exhibit a visible change in the relative magnitude of ODP. While Halon 1211 is known to have a larger impact over a short time horizon (Solomon and Albritton, 1992), the choice of a short time scale did not produce a significant change in its relative impact.

The toxicity impacts show an increasing trend in impact with the increase in the time horizon. For HTP, the average percentage increase from a 20 year to an infinite time horizon of the four options was 52%. The average increase in FAETP and MAETP was nearly 41% and 100% respectively. Finally, the average increase for TETP was found to be 56%.

The results of the sensitivity analysis are comparable to work by Huijbregts et al., 2001 where 181 substances were studied for their behavior in different time horizons. Impacts from metals have a significant contribution in marine ecotoxicity over an infinite time horizon. In a shorter time scale, impact from metals is relatively low. These results can be explained by the fact that substances emitted into the environment demonstrate different impacts over ranges of time frames because of their different environmental residence time.

In the case of metals, disposal activities particularly land-filling, release metals into the environment at extremely slow rates and concentrations (Finnveden and Nielsen, 1999), which can lead to higher cumulative impacts in a long time frame.

The time horizon dependent impact is also attributed to the extremely long "modeled residence time" (Huijbregts et al., 2001) of metals in the environment in the fate exposure models that are used. Although exposure to direct emissions into fresh water is completed in a short time period through mechanisms such as burial in deep freshwater sediment and run-off to the marine compartment, indirect emissions into fresh water from the air and soil compartments lead to a time-dependent impact (Huijbregts et a., 2001).

For the marine environment, the time horizon dependency of impact is especially large because the metals released into other compartments such as soil are modeled to take an extremely long time before they run-off into the marine system. (Cleven et al., 1993; Guinée et al., 1999). The HTP in the model is factored in through different exposure pathways (Huijbregts et al., 2001). The time dependent increase in its magnitude can be very significant if the exposure occurs through marine environment (Huijbregts et al., 2001).

CHAPTER 6

DISCUSSION

Secondary impacts of five remediation alternatives for a hypothetical hydrocarbon contaminated site were analyzed with LCA. LCA was used to quantify secondary impacts related to remediation activities and to identify opportunities to improve remediation design from a sustainability perspective.

The results showed MNA to be the lowest impact option due to limited resource input requirements. Bioventing had a greater environmental impact in comparison to MNA, but it was the lowest impact option among the active remediation approaches examined that also included chemical oxidation, in-situ S/S and ex situ S/S. The input of resources is directly related to the magnitude of impacts. The more a technological approach required energy and resources for treatment, the greater were the impacts. In this respect, ex-situ S/S produced the greatest overall impact among the approaches considered due to the additional resources required for transportation of the backfill and the stabilized soil to an off-site disposal facility.

Contribution analysis showed that the life cycle of material and services used onsite was dominated by processes related to energy use, particularly for the categories: ADP, GWP, AP, PCOP and EP. At the same time aquatic ecotoxicity impact categories were mainly dominated by waste disposal activities. Although disposal activities such as landfilling were the primary contributors of metal emissions, the use of coal (for electricity generation and processing of materials) was also identified as a contributor of metals. This source of metals to the environment means that the environmental impact from energy use was not limited to emissions of global warming gases and resource depletion.

Although the results of impact assessment showed the dominance of MAETP among the impact estimates resulting from use of options (2, 3, 4 and 5) it is noteworthy that the toxicity impacts are modeled using an infinite time horizon. Because metal emissions were identified as major contributors to the toxicity impacts, the combination of their persistent nature and the choice of an infinite time horizon resulted in the dominance of MAETP – as the ocean is the modeled final sink for metals. Also, it was observed that when using shorter time scales (20, 100 and 500 years) the FAETP was greater than MAETP for the four options - (2), (3), (4), and (5). FAETP decreased with time due to removal processes, which in turn deposit the metals into the marine environment causing the increase in MAETP with time.

The overall magnitude of the toxicity impact was found to increase with increasing time horizon due to the future emissions from landfills, which are modeled as lasting for thousands of years in the Ecoinvent database (Ecoinvent, 2000). This explains the long-term nature of the impacts associated with waste disposal activities.

Many processes contributed to GWP. They were related to energy use during either the processing stages of materials used in the remediation processes such as cement, bentonite, steel and PVC or their end use (for example, transportation activities). Although sensitivity analysis showed that the GWP gradually decreases with time, the relative magnitude of the GWP increased when the potential impact for time dependent categories (GWP, ODP, HTP, FWAETP, MAETP and TETP) is characterized in a single time horizon (20, 100 and 500 years).

The infinite time horizon for toxicity impact categories seems intended to capture long term impacts, but the choice of a 100 year time horizon for GWP in the baseline categories leads to an unrealistic dominance of MAETP. Additionally, impact categories such as ADP, PCOP, and EP are diminished in magnitude where fate is either irrelevant or not included. The results of sensitivity analysis did not affect the ranking of the five treatment options. But use of shorter time scales (20, 100 and 500 years) provided a shift in environmental concerns towards categories other than MAETP, such as ADP, GWP, FAETP, PCOP, AD and EP in option (2), (3) and (4).

Since the LCIA phase is designed to interpret inventory results with regard to which environmental interventions are more important than the others in order to draw conclusions for improvement (Saur et al., 1996), it is important to interpret results in a single time scale to justify the relative magnitude of the potential impacts and to have a more meaningful representation.

There are both long term and short term environmental issues associated with remediation activities. It can be useful therefore to assess impacts on a smaller time scale from the perspective of policy making and setting pollution reduction goals for the near future while also recognizing the long term impacts and emissions of persistent substances.

6.1 Limitations in LCA

LCA is a developing field that holds promise for important contributions but currently has important limitations. The impact assessment results are dependent on the models used for characterization. Several assumptions and simplifications can bring errors, incompleteness, and uncertainty in the final results. This study found FAETP and MAETP to be significant toxicity categories for short (20, 100, 500 years) and long (infinite) time horizons respectively. Metal emissions were the main contributors for both. Hydrogen fluoride emissions followed by beryllium emissions were also dominant sources of MAETP in the infinite time horizon. But it must be noted that toxicity assessments coming from the LCIA methods involve some uncertainties. In the case of MAETP (infinite time horizon) there are known errors (overestimation) in the characterization of Hydrogen fluoride (Frischknecht and Jungbluth, 2007) in the CML 2 (2000) method. Factors for some metals such as beryllium are also known to have inaccuracies due to the uncertainty about their average oceanic residence time. This is an important shortcoming especially because this study involves processes that release metals and hydrogen fluoride into the environment.

Fate modeling of metals is also complicated by factors such as persistence, essentiality, bioavailability and speciation. These are currently not taken into account in the fate exposure models (Heijungs et al., 2004). An implication of this is a potential overestimation of toxicity due to metals.

6.2 Limitations of the Study

A hypothetical contaminated site was developed to perform this study. Certain assumptions were made to create a simplified system. While they provided ease and clarity for consideration of the LCA application, the assumptions and simplifications can be a source of uncertainty in the results and how they can be used. Additionally, parameters like site characterization, changes in technology efficiency and the primary impacts from site contaminants are not included in the consideration. It is recognized that these are important factors and the assessment of direct impacts from contamination can be especially significant in decision making. However, the present study lacks these components. Subsequent work is expected to address them.

CHAPTER 7

SUSTAINABLE REMEDIATION

Reduction of risk to human health is a widely used basis for regulatory action and for decision making about contaminated sites (US EPA 1989; US EPA 1996). Other factors that may also be considered are technical suitability, cost and social acceptance (Soesilo and Wilson, 1997). These factors are often focused on reduction of risk at a micro scale as defined by the site's geographic boundaries. The potential broader environmental cost of remediation is largely ignored in the current management practices for contaminated sites. In order to be truly sustainable, decision making must also consider negative impacts of remediation and strive to achieve a balance that addresses the maximum number of parameters (Bardos et al., 2001).

The findings of this work indicate that greater site disturbance, use of equipment, energy and material translate into a higher magnitude of environmental impacts. MNA in this respect was environmentally the most suitable of the options considered. At the same time passive remediation like MNA is known to take a long period to reach regulatory goals. Long remediation times, uncertainty in reaching remediation goals, restricted future land use and risk (real and perceived) from contaminants are some factors that limit application of MNA (US EPA, 1999; Kean et al., 2005). Additionally, a State-regulator's experience with MNA, as well as the existence and understanding of protocols to evaluate MNA proposals can also affect its approval for a site (Kean et al., 2005). But remediation planners should take into consideration the conclusion that MNA causes the least environmental damage from the perspective of the secondary impacts considered in this study. MNA can therefore prove to be more environmentally sustainable at certain sites in the long term. Further, the remediation options that minimize onsite activity and disturbance such as enhanced attenuation (for example, bioremediation) where natural attenuation is boosted by controlled and strategic active remediation approaches (Early et al., 2006), can be more sustainable than some more aggressive approaches because they are less resource intensive and can also reduce total treatment time.

Whether the risk from a certain contaminated site outweighs the wider environmental damage caused by active remediation methods should be evaluated in more detail at a policy or regulatory level to take actions that produce the greatest net environmental benefit.

This study also identified non-renewable energy use as one of the most dominant life cycle stages in all remediation options with regard to secondary impacts. While impact from fossil fuels was clearly most significant in the case of electricity consumption and transportation, production of materials such as cement, steel, hydrogen peroxide and ferrous sulfate was also identified to be energy intensive where use of fossil fuels produced highest impacts. Available conceptual models for sustainability can be applied at these "hot spots" (refer to chapter 4) of environmental impact. For example, Robèrt, et al., 2003, have developed a systems model where two basic mechanisms of meeting sustainability objectives are described as "dematerialization" and "substitution". These mechanisms can be further broken down into practices such as the use of more efficient engines, recycling, use of renewable energy, and use of sustainable materials to optimize a remedial design.

7.1 LCA as a Tool for Sustainability

LCA is often used as a management tool for sustainable development because it is designed to capture environmental considerations of products and services throughout their life cycle. LCA's primary strength lies in its "cradle to grave" perspective. At the same time, the impact assessment methodologies in LCA have been criticized primarily due to their lack of spatial and temporal context (Strandesen et al., 2007; Owen, 1997; Heijungs et al., 2004). This limits the capacity of LCA to clearly assess a system.

Impact assessment in LCA does not specify the location and time of an environmental intervention. The same kinds of interventions are clubbed together regardless of when and where they take place. In part, the aggregation over space and time is necessary for developing a practical tool with wide applicability, at the same time the actual realization of an impact is dependent on local conditions such as the threshold level, background concentration and dose-response curve (Strandesen et al., 2007; Heijungs et al., 2004; Owen, 1997). These factors bring uncertainty in assessment, particularly for categories such as ecotoxicity, human toxicity, photochemical smog and eutrophication (Owen, 1997).

To overcome some of the criticism, impacts are often referred to as "potential impacts" (Guinée and Heijungs, 1993) because they reflect the potential of pollutants to cause damage while the actual realization may depend on site specific factors. LCA results therefore should be viewed as "directional indicators" (Owen, 1997) which can be supplemented further with site specific risk assessment studies. Nevertheless, LCA can well identify material and energy flow in a system and can be used to optimize its efficiency (Owen, 1997).

Additionally, LCA only focuses on the environmental aspect of an activity and says nothing about social and economic aspects. They can be addressed through other available frameworks. These are discussed in the following section.

Therefore LCA should be considered as a tool that is still in its developmental stages and has limitations. And, it only partially addresses the full scope of sustainability. To get a comprehensive analysis other frameworks should also be included.

7.2 Decision Support Approaches for Sustainability

The concept of sustainability is based on the environmental, social and economic aspects of an activity. A few studies in the past have developed frameworks to address this range of aspects in site remediation. Bardos et al., 2001 have contributed in this respect by proposing an overarching, qualitative decision support approach for site remediation. It includes a number of parameters such as risk management, technical suitability of a technology, stakeholder views, long term sustainability and cost. These are identified as several "layers" of decision support system comprised of both extensive site specific data and general information. It was emphasized that management of contaminated land must include a number of relevant "layers" to call it truly sustainable.

A quantitative decision support tool called the REC method (Risk reduction, Environmental merit and Costs) has been developed by Beinat et al., 1997. It addresses the environmental and cost concerns in selection of remediation alternatives at a given site. Each alternative is evaluated based on reduction in risk, environmental effects and cost. Risk is determined at a local scale for humans, agriculture and ecosystems, and the physical environment. The environmental merit is somewhat based on the LCA approach. The selected number of categories are weighted according to the judgment of experts to obtain a single score for each alternative. The costs related to each alternative include initial, operational, replacement and overhead costs. These are based on estimates of expected costs.

The strength of this method lies in the assessment of local impacts and economic aspects along with the wider environmental concerns. However, one of the criticisms of this method can be the lack of sophistication in calculation of environmental merit when compared to the available LCA methods. For example, the processes related to manufacturing of materials used in remediation are not included (Drunen et al., 2000). Additionally, only a small number of emissions are considered (Drunen at al., 2000).

Shakweer and Nathanail, 2003 have developed the Methodology for Remediation Selection (AfrS) for consideration of the environmental, social and economic components in remediation technology selection. The method is quantitative in nature and is based on the LCA approach. It consists of eleven phases: planning and social interpretation, scope definition, preliminary data collection, screening, data collection, analysis, ranking, environmental interpretation, economic interpretation, final interpretation, and evaluation. The stakeholders are involved by holding workshops and focus groups. Their concerns and expectations are solicited through questionnaires. An impact score is obtained for each remediation alternative by assigning weights (based on stakeholders' preferences) to the normalized environmental impacts. The economic aspect is included by dividing the environmental impact saved by the remediation alternative (determined by subtracting the impact of remediation from the impact of contaminants in no action scenario) by the cost of that alternative. The inverse of this figure is added to the impact scores previously obtained. The alternative with the lowest total score is considered as the most suitable.

Although the AfrS is a simple method that includes site specific stakeholder concerns and costs, the simplification and subjectivity in the total score calculation can be the source of uncertainty. This can affect the representativeness of the total score as the criterion for decision making.

Determining the social impacts of an activity is a difficult task that presently has no widely accepted methods. Nevertheless, this field is evolving into more practicable approaches. "Societal LCA" (Hunkeler, 2006) is a promising method that uses labor hours as the "intermediate variable". The method uses LCI data to convert the environmental interventions into labor hours (the hours needed for production, transportation etc.). One prerequisite of this method is the availability of regionally differentiated LCI. The employment hours are then used to determine social indicators such as education and housing. The methodology can be used to identify trade-offs and key areas of substitution between alternatives.

Achieving sustainable remediation that appropriately addresses all three components of sustainability can be difficult as the field of sustainability is currently a developing one. However, various available approaches can be used in a complementary way to strengthen the accuracy of the decision as well as to include maximum number of parameters.

CHAPTER 8

CONCLUSION AND RECOMMENDATIONS

The results of this study show that treatment option (1) MNA produced the lowest environmental impact followed by option (2), bioventing, simply because of lower input of material and energy with MNA. While these options caused less life-cycle environmental damage, the treatment time was longer compared to the timeframes for chemical oxidation, in-situ S/S and ex-situ S/S. This negative time aspect should therefore be balanced with the long term positive reductions in impacts during the decision making process to lead to choices that are protective of human health and the environment not only in the near future but also in the long term. Also, development of better regulatory and technical guidance for implementation of natural attenuation options could result in wider acceptance of these methods because currently several states do not accept natural attenuation as a remediation option.

MAETP was identified as a dominant impact category for options 2, 3, 4 and 5. This is attributed to three factors: persistence of metals, marine environment as the modeled sink for metals and use of an infinite time horizon. Sensitivity analysis showed that when GWP, ODP, HTP, FAETP, MAETP and TETP are characterized in a single shorter time horizon the relative dominance of MAETP changes and the impacts are spread to ADP, GWP, FWATP, PCOP, AP and EP. Further, it is concluded that a single time horizon should be used for characterization of impacts to avoid unrealistic dominance of long term impacts, and to have a more meaningful representation of the relative magnitude of likely impacts.

Many processes involved emission of metals. These were found to be the primary contributors to toxicity impact categories – HTP, FAETP, MAETP and TETP. In the case of MAETP (infinite time horizon), in addition to metals, hydrogen fluoride emissions were significant contributors to impacts. It was noted that the current HF characterization factors for MAETP (infinite time horizon) are overestimated (Frischknecht and Jungbluth, 2007) in the CML 2 (2000) method. That overestimation is another likely reason for the high MAETP. This limitation should be clearly communicated in studies using the CML 2 (2000) method.

Use of fossil energy was clearly the most dominant process contributing to impacts in the life cycle of remediation activities. Based on that conclusion, use of non-renewable sources of energy should be emphasized in the remedial design along with lower-energy consuming options. Also, the LCA results should be supplemented with site specific risk assessments to assess the spatial context of impacts. This leads to the conclusion that while general consideration of the sustainability parameters of alternative remediation options can be useful and informative, decisions for particular sites still must be based on site-specific factors and considerations.

APPENDIX A

INVENTORY OF ENVIRONMENTAL INTERVENTIONS

A.1 MNA

Table A.1 Environmental interventions – MNA

Substance	Compart-ment	Unit	Total
Ammonia	Water	g	42.264
Bauxite, in ground	Raw	kg	1.69056
BOD5, Biological Oxygen Demand	Water	g	42.264
Carbon dioxide	Air	ton	15.54113
Carbon monoxide	Air	kg	417.9635
Chloride	Water	g	84.528
Coal, 29.3 MJ per kg, in ground	Raw	kg	1.436976
COD, Chemical Oxygen Demand	Water	g	169.056
Dinitrogen monoxide	Air	kg	2.88
Energy, unspecified	Raw	GJ	14.3275
Gas, natural, 36.6 MJ per m3, in ground	Raw	m3	274.716
Hydrocarbons, unspecified	Air	kg	12.76373
Hydrocarbons, unspecified	Water	g	84.528
Hydrogen	Air	g	16.06032
Iron ore, in ground	Raw	g	845.28
Metallic ions, unspecified	Water	g	4.2264
Mineral waste	Waste	g	591.696
Nitrogen oxides	Air	kg	106.5751
Hydrogen chloride	Air	g	4.2264
Hydrogen	Water	g	4.2264
Oil, crude, 42.7 MJ per kg, in ground	Raw	ton	4.348966
Particulates, SPM	Air	kg	1.26792
Slags	Waste	g	211.32
Soot	Air	kg	1.008
Sulfur dioxide	Air	kg	6.73704
Transformation, to industrial area	Raw	cm2	101.011
VOC, volatile organic compounds	Air	kg	59.76
Water, unspecified natural origin/kg	Raw	kg	232.452

A.2 BIOVENTING

Table A.2 Environmental interventions - Bioventing

Substance	Compartment	Unit	Total
Acenaphthene	Water	µg	10.04555
Acenaphthylene	Water	ng	628.2505
Acetaldehyde	Air	mg	48.63724
Acetic acid	Air	g	27.66218
Acetic acid	Water	g	1.559906
Acetone	Air	mg	64.78152
Acidity, unspecified	Water	g	2.167674
Aclonifen	Soil	µg	69.59408
Acrolein	Air	mg	158.6922
Actinides, radioactive, unspecified	Air	µBq	46.59616
Actinides, radioactive, unspecified	Water	Bq	5.293902
Aerosols, radioactive, unspecified	Air	mBq	670.4243
Aldehydes, unspecified	Air	g	35.95187
Aluminium, 24% in bauxite, 11% in crude ore, in ground	Raw	g	139.0045
Aluminum	Air	g	9.318603
Aluminum	Water	g	174.0834
Aluminum	Soil	g	1.345336
Ammonia	Air	g	79.70154
Ammonia	Water	g	24.74295
Ammonium carbonate	Air	mg	1.075065
Ammonium, ion	Water	g	7.58382
Anhydrite, in ground	Raw	mg	605.1136
Antimony	Air	mg	74.18734
Antimony	Water	mg	613.5663
Antimony	Soil	ng	229.5165
Antimony-122	Water	mBq	2.991494
Antimony-124	Air	µBq	7.420073
Antimony-124	Water	mBq	855.0194
Antimony-125	Air	µBq	77.43469
Adsorbable Organic Halogen as Cl	Water	mg	108.9388
Argon-41	Air	Bq	975.9246
Arsenic	Air	mg	588.9244
Arsenic	Soil	µg	416.1314
Arsenic, ion	Water	mg	175.1214
Atrazine	Soil	µg	1.286909
Barite	Water	g	8.849345
Barite, 15% in crude ore, in ground	Raw	g	268.1289
Barium	Air	mg	21.49309
Barium	Water	g	4.19415
Barium	Soil	mg	425.8163
Barium-140	Air	mBq	5.037012
Barium-140	Water	mBq	13.10433
Basalt, in ground	Raw	g	448.3045
Bauxite, in ground	Raw	g	704.4
Bentazone	Soil	µg	35.44314
Benzaldehyde	Air	µg	24.59921
Benzene	Air	g	12.56205
Benzene	Water	g	18.18234
Benzene, ethyl-	Air	mg	49.20372
Benzene, ethyl-	Water	mg	38.76775
Benzene, hexachloro-	Air	µg	27.16521
Benzene, pentachloro-	Air	µg	12.04117
Benzo(a)pyrene	Air	mg	4.538589
Beryllium	Air	mg	65.21245
Beryllium	Water	mg	16.04215
BOD5, Biological Oxygen Demand	Water	g	639.4363
Borax, in ground	Raw	mg	45.18177
Boron	Air	g	1.380934
Boron	Water	g	429.9953
Boron	Soil	mg	17.14415
Bromate	Water	g	6.749302
Bromine	Air	mg	76.09999
Bromine	Water	g	1.834422
Butadiene	Air	ng	12.38131

Substance	Compartment	Unit	Total
Butene	Air	mg	35.5062
Butene	Water	µg	39.19127
Cadmium	Air	mg	131.1362
Cadmium	Soil	µg	344.8863
Cadmium, ion	Water	g	1.958647
Calcite, in ground	Raw	kg	49.10338
Calcium	Air	mg	288.9934
Calcium	Soil	g	5.625857
Calcium, ion	Water	kg	1.502775
Carbetamide	Soil	µg	13.47884
Carbon	Soil	g	7.767346
Carbon-14	Air	Bq	3295.927
Carbon dioxide	Air	kg	6475.47
Carbon dioxide, biogenic	Air	kg	14.05026
Carbon dioxide, fossil	Air	kg	12681.91
Carbon dioxide, in air	Raw	kg	9.628767
Carbon disulfide	Air	mg	939.1178
Carbon monoxide	Air	kg	180.6149
Carbon monoxide, biogenic	Air	g	8.732309
Carbon monoxide, fossil	Air	g	543.1286
Carbonate	Water	g	42.61469
Carboxylic acids, unspecified	Water	g	6.949605
Cerium-141	Air	mBq	1.221086
Cerium-141	Water	mBq	5.239326
Cerium-144	Water	mBq	1.595022
Cesium	Water	mg	1.61504
Cesium-134	Air	µBq	58.48215
Cesium-134	Water	mBq	585.912
Cesium-136	Water	µBq	929.8782
Cesium-137	Air	mBq	1.036698
Cesium-137	Water	Bq	609.3999
Chlorate	Water	g	56.91951
Chloride	Water	kg	8.417851
Chloride	Soil	g	12.49509
Chlorinated solvents, unspecified	Water	mg	817.8442
Chlorine	Air	g	94.402
Chlorine	Water	mg	122.0592
Chloroform	Water	pg	118.1855
Chlorothalonil	Soil	µg	969.7569
Chromate	Water	mg	104.0982
Chromium	Air	g	1.328069
Chromium	Water	g	1.920278
Chromium	Soil	mg	17.12991
Chromium-51	Air	µBq	78.24695
Chromium-51	Water	Bq	1.247198
Chromium VI	Air	mg	10.84266
Chromium VI	Water	mg	880.4097
Chromium VI	Soil	mg	48.67564
Chromium, 25.5 in chromite, 11.6% in crude ore, in ground	Raw	g	126.1275
Chromium, ion	Water	mg	21.88126
Chrysotile, in ground	Raw	g	1.277518
Cinnabar, in ground	Raw	mg	117.4977
Clay, bentonite, in ground	Raw	kg	600.0608
Clay, unspecified, in ground	Raw	kg	22.11393
Coal, 26.4 MJ per kg, in ground	Raw	kg	4647.751
Coal, 29.3 MJ per kg, in ground	Raw	g	598.74
Coal, brown, in ground	Raw	kg	53.12082
Coal, hard, unspecified, in ground	Raw	kg	63.37895
Cobalt	Air	mg	215.7066
Cobalt	Water	mg	606.0033
Cobalt	Soil	µg	284.5697
Cobalt-57	Water	mBq	29.51784
Cobalt-58	Air	µBq	108.9621
Cobalt-58	Water	Bq	7.684659
Cobalt-60	Air	µBq	962.5788
Cobalt-60	Water	Bq	6.391397
Cobalt, in ground	Raw	µg	377.1927
COD, Chemical Oxygen Demand	Water	kg	2.240171
Colemanite, in ground	Raw	mg	196.3046
Copper	Air	mg	339.4291

Substance	Compart -ment	Unit	Total
Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	Raw	g	8.083119
Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore, in ground	Raw	g	37.84939
Copper, 1.42% in sulfide, Cu 0.81% and Mo 8.2E-3% in crude ore, in ground	Raw	g	10.02642
Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore, in ground	Raw	g	49.80082
Copper, ion	Water	g	2.764131
Cumene	Air	g	7.458449
Cumene	Water	g	17.92254
Cyanide	Air	mg	15.6399
Cyanide	Water	mg	267.5497
Cypermethrin	Soil	ng	319.6813
Diatomite, in ground	Raw	µg	24.59126
Dichromate	Water	mg	1.271443
Dinitrogen monoxide	Air	kg	1.305984
Dinoseb	Soil	µg	263.5761
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	Air	ng	970.6626
DOC, Dissolved Organic Carbon	Water	g	232.7341
Dolomite, in ground	Raw	g	7.902862
Energy, from hydro power	Raw	MJ	6671.269
Energy, gross calorific value, in biomass	Raw	MJ	112.2242
Energy, kinetic, flow, in wind	Raw	MJ	39.64885
Energy, potential, stock, in barrage water	Raw	MJ	196.8487
Energy, solar	Raw	kJ	564.1599
Ethane	Air	g	5.667938
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	Air	mg	11.96282
Ethane, 1,2-dichloro-	Air	g	1.52572
Ethane, 1,2-dichloro-	Water	mg	28.41612
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	Air	mg	1.326052
Ethane, hexafluoro-, HFC-116	Air	mg	2.083574
Ethanol	Air	mg	86.5438
Ethene	Air	g	4.877319
Ethene	Water	g	7.453653
Ethene, chloro-	Air	g	2.902301
Ethene, chloro-	Water	mg	63.41401
Ethene, tetrachloro-	Air	mg	151.06
Ethene, trichloro-	Air	mg	149.8123
Ethylene diamine	Air	ng	156.7545
Ethylene diamine	Water	ng	380.0109
Ethylene oxide	Air	mg	95.17276
Ethylene oxide	Water	µg	12.29227
Ethyne	Air	mg	43.44156
Feldspar, in ground	Raw	mg	1.38444
Fenpiclonil	Soil	µg	40.5546
Fluoride	Water	g	19.77447
Fluoride	Soil	mg	75.53916
Fluorine	Air	mg	8.493996
Fluorine, 4.5% in apatite, 1% in crude ore, in ground	Raw	mg	492.7876
Fluorine, 4.5% in apatite, 3% in crude ore, in ground	Raw	mg	221.0649
Fluorspar, 92%, in ground	Raw	g	14.53351
Fluosilicic acid	Air	mg	2.435582
Fluosilicic acid	Water	mg	4.38332
Formaldehyde	Air	g	1.374802
Formaldehyde	Water	mg	935.5783
Gas, mine, off-gas, process, coal mining/m3	Raw	l	621.7552

Substance	Compart-ment	Unit	Total
Gas, natural, 46.8 MJ per kg, in ground	Raw	kg	795.8031
Gas, natural, in ground	Raw	m3	76.89336
Glutaraldehyde	Water	mg	1.092512
Glyphosate	Soil	mg	3.802737
Granite, in ground	Raw	mg	51.21927
Gravel, in ground	Raw	kg	1354.611
Gypsum, in ground	Raw	g	8.078425
Heat, waste	Air	MJ	5893.113
Heat, waste	Water	MJ	91.14599
Heat, waste	Soil	MJ	4.70535
Helium	Air	mg	90.51848
Heptane	Air	mg	354.8981
Hexane	Air	g	1.047562
Hydrocarbons, aliphatic, alkanes, cyclic	Air	mg	1.576469
Hydrocarbons, aliphatic, alkanes, unspecified	Air	g	1.69768
Hydrocarbons, aliphatic, alkanes, unspecified	Water	mg	209.9552
Hydrocarbons, aliphatic, unsaturated	Air	mg	383.5771
Hydrocarbons, aliphatic, unsaturated	Water	mg	19.38048
Hydrocarbons, aromatic	Air	g	1.750262
Hydrocarbons, aromatic	Water	mg	876.7071
Hydrocarbons, chlorinated	Air	mg	242.8947
Hydrocarbons, unspecified	Air	kg	5.31822
Hydrocarbons, unspecified	Water	g	44.79576
Hydrogen	Air	g	49.31565
Hydrogen	Water	g	1.761
Hydrogen-3, Tritium	Air	Bq	18574.55
Hydrogen-3, Tritium	Water	kBq	1403.559
Hydrogen chloride	Air	g	815.9611
Hydrogen fluoride	Air	g	112.3295

Substance	Compart-ment	Unit	Total
Hydrogen sulfide	Air	g	6.544742
Hydrogen sulfide	Water	mg	138.5829
Hydroxide	Water	mg	3.97245
Hypochlorite	Water	mg	84.85511
Iodide	Water	mg	168.119
Iodine	Air	mg	41.19202
Iodine-129	Air	Bq	3.259235
Iodine-131	Air	Bq	386.476
Iodine-131	Water	mBq	179.0896
Iodine-133	Air	mBq	6.022698
Iodine-133	Water	mBq	8.226609
Iron	Air	mg	424.4083
Iron	Water	g	629.2337
Iron	Soil	g	12.66404
Iron-59	Water	mBq	2.261671
Iron ore, in ground	Raw	g	352.2
Iron, 46% in ore, 25% in crude ore, in ground	Raw	kg	3.130158
Iron, ion	Water	g	188.926
Isocyanic acid	Air	mg	1.895285
Kaolinite, 24% in crude ore, in ground	Raw	g	1.297413
Kerosene	Air	g	4.050097
Kieserite, 25% in crude ore, in ground	Raw	mg	7.747055
Krypton-85	Air	Bq	3054.07
Krypton-85m	Air	Bq	121.5548
Krypton-87	Air	Bq	53.3261
Krypton-88	Air	Bq	50.41525
Krypton-89	Air	Bq	11.49578
Lanthanum-140	Air	µBq	430.4936
Lanthanum-140	Water	mBq	13.9572
Lead	Air	mg	676.8961
Lead	Water	mg	526.7754
Lead	Soil	mg	5.533871
Lead-210	Air	Bq	16.76652
Lead-210	Water	Bq	15.75468
Lead, 5%, in sulfide, Pb 2.97% and Zn 5.34% in crude ore, in ground	Raw	g	17.72199
Limestone, in ground	Raw	kg	267.9765
Linuron	Soil	µg	538.5718

Substance	Compartment	Unit	Total
Magnesite, 60% in crude ore, in ground	Raw	g	44.54402
Magnesium	Air	mg	334.5735
Magnesium	Water	g	107.9827
Magnesium	Soil	mg	931.0505
Magnesium, 0.13% in water	Raw	mg	1.895234
Mancozeb	Soil	mg	1.262524
Manganese	Air	g	1.807027
Manganese	Water	g	366.0393
Manganese	Soil	mg	92.91284
Manganese-54	Air	µBq	40.0711
Manganese-54	Water	mBq	465.2573
Manganese, 35.7% in sedimentary deposit, 14.2% in crude ore, in ground	Raw	g	14.0955
Mercury	Air	mg	354.529
Mercury	Water	mg	17.89918
Mercury	Soil	µg	42.35282
Metaldehyde	Soil	µg	2.770347
Metallic ions, unspecified	Water	g	5.721809
Metals, unspecified	Air	g	1.691709
Methane	Air	kg	26.92972
Methane, biogenic	Air	g	4.476814
Methane, bromochlorodifluoro-, Halon 1211	Air	mg	1.179999
Methane, bromotrifluoro-, Halon 1301	Air	µg	988.0451
Methane, chlorodifluoro-, HCFC-22	Air	mg	5.792827
Methane, dichloro-, HCC-30	Air	mg	672.3112
Methane, dichloro-, HCC-30	Water	mg	21.55943
Methane, dichlorodifluoro-, CFC-12	Air	µg	6.566853

Substance	Compartment	Unit	Total
Methane, fossil	Air	g	916.6421
Methane, monochloro-, R-40	Air	ng	9.617349
Methane, tetrachloro-, CFC-10	Air	mg	359.2096
Methane, tetrafluoro-, FC-14	Air	mg	18.75217
Methane, trichlorofluoro-, CFC-11	Air	pg	191.8678
Methane, trifluoro-, HFC-23	Air	ng	37.60447
Methanol	Air	g	17.49548
Methanol	Water	mg	296.8493
Metolachlor	Soil	mg	3.895438
Metribuzin	Soil	µg	44.37424
Mineral waste	Waste	g	246.54
Molybdenum	Air	mg	4.282875
Molybdenum	Water	mg	112.7119
Molybdenum	Soil	µg	150.7722
Molybdenum-99	Water	mBq	4.812142
Molybdenum, 0.010% in sulfide, Mo 8.2E-3% and Cu 1.83% in crude ore, in ground	Raw	mg	925.4837
Molybdenum, 0.014% in sulfide, Mo 8.2E-3% and Cu 0.81% in crude ore, in ground	Raw	mg	131.6978
Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36% in crude ore, in ground	Raw	g	5.016103
Molybdenum, 0.025% in sulfide, Mo 8.2E-3% and Cu 0.39% in crude ore, in ground	Raw	mg	483.2394

Substance	Compart-ment	Unit	Total
Monoethanolamine	Air	mg	8.362086
N-Nitrodimethylamine	Air	mg	33.48963
Naphthalene	Air	mg	8.547607
Napropamide	Soil	µg	4.902675
Nickel	Air	g	2.17972
Nickel	Soil	mg	8.3428
Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore, in ground	Raw	g	1.826183
Nickel, 1.98% in silicates, 1.04% in crude ore, in ground	Raw	g	319.5215
Nickel, ion	Water	g	2.396909
Niobium-95	Air	µBq	4.756789
Niobium-95	Water	mBq	52.64716
Nitrate	Air	µg	380.1654
Nitrate	Water	g	49.95415
Nitrite	Water	mg	295.6939
Nitrogen	Water	g	3.44848
Nitrogen oxides	Air	kg	90.16639
Nitrogen, organic bound	Water	mg	650.4092
NMVOC, non-methane volatile organic compounds, unspecified origin	Air	kg	9.012223
Noble gases, radioactive, unspecified	Air	kBq	31313.29
Oil, crude, 42.7 MJ per kg, in ground	Raw	kg	1812.069
Oil, crude, in ground	Raw	kg	61.72331
Oils, biogenic	Soil	mg	308.2935
Oils, unspecified	Water	g	856.5838
Oils, unspecified	Soil	g	105.9489
Olivine, in ground	Raw	mg	218.0999
Orbencarb	Soil	µg	239.4633
Organic substances, unspecified	Air	g	148.6063
Organic substances, unspecified	Water	g	202.9305
Ozone	Air	g	1.194746
PAH, polycyclic aromatic hydrocarbons	Water	mg	18.71404
Paraffins	Air	µg	1.898473
Paraffins	Water	µg	5.509555
Particulates, < 10 um	Air	kg	2.40506
Particulates, < 2.5 um	Air	g	102.4969
Particulates, > 10 um	Air	g	229.5176
Particulates, > 2.5 um, and < 10um	Air	g	130.2327
Particulates, SPM	Air	g	528.3
Particulates, unspecified	Air	kg	11.7706
Pd, Pd 2.0E-4%, Pt 4.8E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	Raw	µg	68.74711
Pd, Pd 7.3E-4%, Pt 2.5E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	Raw	µg	165.2194
Peat, in ground	Raw	g	18.67254
Pentane	Air	g	3.252065
Phenol	Air	mg	524.8496
Phenol	Water	mg	410.0012
Phenol, pentachloro-	Air	mg	1.813392
Phosphate	Water	g	63.55316
Phosphorus	Air	mg	14.3502
Phosphorus	Water	g	43.14296
Phosphorus	Soil	mg	67.57832
Phosphorus, 18% in apatite, 12% in crude ore, in ground	Raw	g	1.28103
Phosphorus, 18% in apatite, 4% in crude ore, in ground	Raw	g	1.97115
Pirimicarb	Soil	µg	3.359714
Platinum	Air	ng	379.3138
Plutonium-238	Air	nBq	444.6124
Plutonium-alpha	Air	µBq	1.019217
Polonium-210	Air	Bq	29.39854

Substance	Compart-ment	Unit	Total
Polychlorinated biphenyls	Air	µg	41.9817
Potassium	Air	mg	717.7621
Potassium	Soil	mg	437.081
Potassium-40	Air	Bq	3.962839
Potassium-40	Water	Bq	13.36234
Potassium, ion	Water	g	72.36523
Propanal	Air	µg	24.59921
Propane	Air	g	3.202278
Propene	Air	g	2.87907
Propene	Water	g	6.602261
Propionic acid	Air	mg	13.31361
Propylene oxide	Air	µg	712.9128
Propylene oxide	Water	mg	1.715446
Protactinium-234	Air	mBq	504.8246
Protactinium-234	Water	Bq	9.348605
Pt, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	Raw	µg	1.999826
Pt, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	Raw	µg	7.169082
Radioactive species, alpha emitters	Water	mBq	17.24034
Radioactive species, Nuclides, unspecified	Water	Bq	3174.391
Radioactive species, other beta emitters	Air	Bq	39.48737
Radioactive species, unspecified	Air	Bq	2.22E+08
Radium-224	Water	Bq	80.75199
Radium-226	Air	Bq	20.57079
Radium-226	Water	Bq	5956.637
Radium-228	Air	Bq	6.278975
Radium-228	Water	Bq	161.504
Radon-220	Air	mBq	81.73546
Radon-222	Air	kBq	67002.62
Rhenium, in crude ore, in ground	Raw	µg	6.209954
Rubidium	Water	mg	16.51172
Ruthenium-103	Air	µBq	1.045098
Ruthenium-103	Water	mBq	1.015405
Rutile, in ground	Raw	mg	1.38059
Sand, unspecified, in ground	Raw	g	13.58919
Scandium	Air	µg	108.13
Scandium	Water	mg	27.22074
Selenium	Air	g	1.134206
Selenium	Water	mg	35.78929
Shale, in ground	Raw	g	1.716651
Silicon	Air	g	1.382401
Silicon	Water	kg	1.545741
Silicon	Soil	g	1.17677
Silicon tetrafluoride	Air	µg	14.90272
Silver	Air	µg	7.178444
Silver	Soil	µg	199.9488
Silver-110	Air	µBq	10.35772
Silver-110	Water	Bq	6.054255
Silver, 0.01% in crude ore, in ground	Raw	µg	236.0037
Silver, ion	Water	mg	2.699227
Slags	Waste	g	88.05
Sodium	Air	mg	242.9495
Sodium	Soil	g	1.720386
Sodium-24	Water	mBq	36.40995
Sodium chlorate	Air	µg	204.5022
Sodium chloride, in ground	Raw	kg	117.2707
Sodium dichromate	Air	µg	343.4443
Sodium formate	Air	µg	551.0297
Sodium formate	Water	mg	1.323815
Sodium sulphate, various forms, in ground	Raw	g	3.993094
Sodium, ion	Water	kg	2.67973
Solids, inorganic	Water	g	917.7253
Solved solids	Water	kg	42.88297
Soot	Air	g	420
Stibnite, in ground	Raw	µg	2.555563
Strontium	Air	mg	24.62881
Strontium	Water	g	11.91184

Substance	Compart-ment	Unit	Total
Strontium-89	Water	mBq	109.7307
Strontium-90	Water	Bq	10592.86
Styrene	Air	µg	23.06931
Sulfate	Air	g	456.7251
Sulfate	Water	kg	6.753185
Sulfide	Water	mg	42.20431
Sulfite	Water	mg	232.3917
Sulfur	Water	mg	279.4816
Sulfur	Soil	mg	995.7802
Sulfur dioxide	Air	kg	4.999458
Sulfur hexafluoride	Air	mg	20.87439
Sulfur oxides	Air	kg	95.77079
Sulfur, in ground	Raw	g	42.80429
Sulfuric acid	Water	g	106.6148
Suspended solids, unspecified	Water	kg	19.03548
Sylvite, 25 % in sylvinite, in ground	Raw	g	560.5829
t-Butyl methyl ether	Air	mg	30.77268
t-Butyl methyl ether	Water	mg	6.58138
Talc, in ground	Raw	g	1.062401
Tebutam	Soil	µg	11.61867
Technetium-99m	Water	mBq	111.77
Teflubenzuron	Soil	µg	2.954999
Tellurium-123m	Water	mBq	78.176
Tellurium-132	Water	µBq	278.6325
Thallium	Air	µg	510.9986
Thallium	Water	mg	2.692212
Thorium	Air	µg	160.4407
Thorium-228	Air	mBq	970.1294
Thorium-228	Water	Bq	323.0773
Thorium-230	Air	Bq	1.897568
Thorium-230	Water	Bq	1275.526
Thorium-232	Air	Bq	1.103899
Thorium-232	Water	Bq	2.363856
Thorium-234	Air	mBq	504.9702
Thorium-234	Water	Bq	9.350161
Tin	Air	mg	7.623544
Tin	Soil	µg	591.9064
Tin, 79% in cassiterite, 0.1% in crude ore, in ground	Raw	mg	283.9251
Tin, ion	Water	mg	119.7535
Titanium	Air	Mg	32.43315
Titanium	Soil	mg	3.520201
Titanium, ion	Water	g	5.142979
TOC, Total Organic Carbon	Water	g	233.2491
Toluene	Air	g	2.335402
Toluene	Water	mg	211.0229
Tributyltin compounds	Water	mg	3.56591
Triethylene glycol	Water	mg	14.48872
Tungsten	Water	mg	30.62594
Ulexite, in ground	Raw	mg	19.21818
Uranium	Air	µg	209.3993
Uranium-234	Air	Bq	5.917057
Uranium-234	Water	Bq	11.21833
Uranium-235	Air	mBq	286.0673
Uranium-235	Water	Bq	18.51024
Uranium-238	Air	Bq	8.755087
Uranium-238	Water	Bq	36.07653
Uranium alpha	Air	Bq	27.50385
Uranium alpha	Water	Bq	538.5256
Uranium, 2291 GJ per kg, in ground	Raw	g	18.35138
Uranium, in ground	Raw	g	2.41499
Vanadium	Air	mg	391.511
Vanadium	Soil	µg	100.7594
Vanadium, ion	Water	mg	511.0175
Vermiculite, in ground	Raw	mg	14.98636
VOC, volatile organic compounds	Air	kg	24.9
VOC, volatile organic compounds, unspecified origin	Water	mg	588.5065
Volume occupied, final repository for low-active radioactive waste	Raw	cm3	4.28661
Volume occupied, final repository for radioactive waste	Raw	cm3	1.014063
Volume occupied, reservoir	Raw	m3day	904.5295

Substance	Compart -ment	Unit	Total
Waste, solid	Waste	kg	2143.59
water	Air	g	12.90975
Water, cooling, unspecified natural origin/m3	Raw	m3	14.51852
Water, lake	Raw	1	15.71737
Water, river	Raw	m3	1.021967
Water, salt, ocean	Raw	1	140.4768
Water, salt, sole	Raw	1	19.76458
Water, turbine use, unspecified natural origin	Raw	m3	1189.74
Water, unspecified natural origin/kg	Raw	kg	96.855
Water, unspecified natural origin/m3	Raw	m3	8.575944
Water, well, in ground	Raw	m3	4.790703
Wood and wood waste, 9.5 MJ per kg	Raw	kg	3.008591
Wood, hard, standing	Raw	1	1.085159
Wood, soft, standing	Raw	1	10.22211

Substance	Compart -ment	Unit	Total
Xenon-131m	Air	Bq	241.2697
Xenon-133	Air	Bq	7530.248
Xenon-133m	Air	Bq	35.93438
Xenon-135	Air	Bq	3098.555
Xenon-135m	Air	Bq	1809.041
Xenon-137	Air	Bq	31.52898
Xenon-138	Air	Bq	290.3507
Xylene	Air	g	2.594745
Xylene	Water	mg	166.0151
Zinc	Air	mg	530.3875
Zinc	Soil	mg	153.7119
Zinc-65	Air	µBq	200.0848
Zinc-65	Water	mBq	493.6365
Zinc 9%, in sulfide, Zn 5.34% and Pb 2.97% in crude ore, in ground	Raw	g	75.49876
Zinc, ion	Water	g	3.060626
Zirconium	Air	µg	63.52058
Zirconium-95	Air	µBq	195.5753
Zirconium-95	Water	mBq	5.716449

A.3 CHEMICAL OXIDATION

Table A.3 Environmental interventions - Chemical oxidation

Substance	Compart -ment	Unit	Total
Acenaphthene	Water	µg	346.0132
Acenaphthylene	Water	mg	205.3274
Acetaldehyde	Air	g	4.866399
Acetic acid	Air	g	62.96913
Acetic acid	Water	g	1.884182
Acetone	Air	g	5.415913
Acidity, unspecified	Water	g	29.91929
Acids, unspecified	Water	mg	213.396
Aclonifen	Soil	mg	1.478794
Acrolein	Air	mg	2.371561

Substance	Compart -ment	Unit	Total
Actinides, radioactive,	Air	mBq	1.931185
Aerosols, radioactive, unspecified	Air	Bq	36.98052
Aldehydes, unspecified	Air	g	136.6499
Aluminium, 24% in bauxite, 11% in crude ore, in ground	Raw	kg	65.21028

Substance	Compartment	Unit	Total
Aluminum	Water	kg	46.92507
Aluminum	Soil	g	49.1653
Americium-241	Air	mBq	375.2137
Americium-241	Water	Bq	49.43292
Ammonia	Air	g	942.6415
Ammonia	Water	g	9.75155
Ammonia, as N	Water	g	15.34247
Ammonium carbonate	Air	mg	3.682696
Ammonium, ion	Water	g	45.96207
Anhydrite, in ground	Raw	g	12.55935
Antimony	Air	mg	183.1738
Antimony	Water	g	21.39956
Antimony	Soil	µg	5.393527
Antimony-124	Air	mBq	5.754127
Antimony-124	Water	Bq	76.07669
Antimony-125	Air	mBq	3.007951
Antimony-125	Water	Bq	36.8797
AOX, Adsorbable Organic Halogen as Cl	Water	mg	190.0326
Argon-41	Air	Bq	67590.95
Arsenic	Air	g	2.844264
Arsenic	Soil	mg	19.32599
Arsenic, ion	Water	g	36.99641
Atrazine	Soil	µg	88.84096
Barite	Water	g	735.6077
Barite, 15% in crude ore, in ground	Raw	kg	7.321033
Barium	Air	g	1.926038
Barium	Water	g	350.2228
Barium	Soil	g	18.65488
Barium-140	Air	mBq	228.6141
Barium-140	Water	mBq	636.495
Baryte, in ground	Raw	g	707.5666
Basalt, in ground	Raw	kg	11.90085
Bauxite, in ground	Raw	kg	1.54287
Bentazone	Soil	µg	753.1262
Benzaldehyde	Air	µg	263.3248
Benzene	Air	g	109.2961
Benzene	Water	g	36.75133
Benzene, chloro-	Water	ng	14.80085
Benzene, ethyl-	Air	g	4.51761
Benzene, ethyl-	Water	g	1.491769
Benzene, pentachloro-	Air	mg	2.415325
Benzo(a)pyrene	Air	mg	209.7002
Beryllium	Air	mg	28.23526
Beryllium	Water	mg	660.0494
BOD5, Biological Oxygen Demand	Water	kg	55.06643
Borax, in ground	Raw	g	1.515869
Boron	Water	g	124.8434
Boron	Soil	mg	704.4092
Bromate	Water	g	14.236
Bromine	Air	g	6.20128
Bromine	Water	g	62.25213
Butadiene	Air	ng	194.1011
Butane	Air	g	154.2717
Butene	Air	g	3.046414
Butene	Water	g	3.791683
Cadmium	Air	mg	956.7638
Cadmium	Soil	mg	9.914306
Cadmium-109	Water	mBq	1.4244
Cadmium, ion	Water	g	21.52435
Calcite, in ground	Raw	kg	1163.196
Calcium	Air	g	69.0773
Calcium	Soil	g	214.4249
Calcium, ion	Water	kg	51.74454
Carbetamide	Soil	µg	319.7633
Carbon	Soil	g	150.7271
Carbon-14	Air	Bq	186170.4
Carbon-14	Water	Bq	2501.425
Carbon dioxide	Air	kg	5691.146
Carbon dioxide, biogenic	Air	kg	874.1139
Carbon dioxide, fossil	Air	kg	15908.74
Carbon dioxide, in air	Raw	kg	259.6327
Carbon disulfide	Air	g	777.2823
Carbon monoxide	Air	kg	98.39732
Carbon monoxide, biogenic	Air	g	495.8745
Carbon monoxide, fossil	Air	kg	84.56602
Carbonate	Water	g	232.1913
Carboxylic acids	Water	g	244.0124

Substance	Compartment	Unit	Total
Cerium-144	Air	Bq	3.990409
Cerium-144	Water	Bq	1131.655
Cesium	Water	mg	62.29017
Cesium-134	Air	Bq	14.26196
Cesium-134	Water	Bq	2561.419
Cesium-137	Air	Bq	27.5516
Cesium-137	Water	Bq	52672.67
Chlorate	Water	g	111.4931
Chloride	Water	kg	107.3534
Chloride	Soil	g	672.5007
Chlorinated solvents, unspecified	Water	mg	306.4143
Chlorine	Air	g	91.41353
Chlorine	Water	g	2.709062
Chloroform	Air	mg	2.820477
Chloroform	Water	mg	13.22388
Chlorothalonil	Soil	mg	53.6833
Chromate	Water	mg	2.826026
Chromium	Air	g	122.625
Chromium	Water	mg	40.56676
Chromium	Soil	mg	600.8085
Chromium-51	Air	mBq	73.1671
Chromium-51	Water	Bq	49.52136
Chromium VI	Air	g	2.970836
Chromium VI	Water	g	674.3016
Chromium VI	Soil	g	1.869348
Chromium, 25.5 in chromite, 11.6% in crude ore, in ground	Raw	kg	42.48514
Chromium, in ground	Raw	g	42.21826
Chromium, ion	Water	g	209.9792
Chrysotile, in ground	Raw	g	2.698194
Cinnabar, in ground	Raw	mg	248.3561
Clay, bentonite, in ground	Raw	kg	566.0616
Clay, unspecified, in ground	Raw	kg	423.504
Coal, 18 MJ per kg, in ground	Raw	kg	566.2505
Coal, 26.4 MJ per kg, in ground	Raw	kg	29.48889
Coal, 29.3 MJ per kg, in ground	Raw	g	319.328
Coal, brown	Raw	kg	717.7061

Substance	Compartment	Unit	Total
Coal, brown, in ground	Raw	kg	1685.447
Cobalt	Air	g	4.01627
Cobalt	Water	g	239.6148
Cobalt	Soil	mg	2.19655
Cobalt-57	Air	µBq	34.59583
Cobalt-57	Water	Bq	1.131537
Cobalt-58	Air	mBq	575.5411
Cobalt-58	Water	Bq	537.8423
Cobalt-60	Air	mBq	880.361
Cobalt-60	Water	Bq	11197.48
Cobalt, in ground	Raw	mg	6.113762
COD, Chemical Oxygen Demand	Water	kg	85.6988
Colemanite, in ground	Raw	g	4.401961
Copper	Air	g	16.19365
Copper	Soil	g	1.978198
Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	Raw	g	213.4413
Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore, in ground	Raw	kg	1.182779
Copper, 1.42% in sulfide, Cu 0.81% and Mo 8.2E-3% in crude ore, in ground	Raw	g	313.3218
Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore, in ground	Raw	kg	1.556256
Copper, in ground	Raw	g	516.2806
Copper, ion	Water	kg	1.175093
Cumene	Air	g	10.98711
Cumene	Water	g	26.4019
Curium-242	Air	µBq	1.980884
Curium-244	Air	µBq	17.98364
Curium alpha	Air	mBq	595.5773
Curium alpha	Water	Bq	65.51351
Cyanide	Air	g	4.305718
Cyanide	Water	g	229.3933

Substance	Compartment	Unit	Total
Cypermethrin	Soil	µg	8.490847
Diatomite, in ground	Raw	µg	913.6749
Dinitrogen monoxide	Air	kg	1.049445
Dinoseb	Soil	mg	14.59091
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	Air	µg	31.44216
DOC, Dissolved Organic Carbon	Water	kg	28.17813
Dolomite, in ground	Raw	kg	7.041258
Energy, from hydro power	Raw	MJ	38.07802
Energy, gross calorific value, in biomass	Raw	MJ	2907.628
Energy, kinetic, flow, in wind	Raw	MJ	1233.094
Energy, potential, stock, in barrage water	Raw	MJ	12527.12
Energy, solar	Raw	MJ	16.64294
Energy, unspecified	Raw	MJ	3183.888
Ethane	Air	g	520.8877
Ethane, 1,1,1-trichloro-, HCFC-140	Water	µg	2.83219
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	Air	mg	698.6011
Ethane, 1,2-dichloro-	Air	g	5.838423
Ethane, 1,2-dichloro-	Water	mg	46.23056
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	Air	mg	444.6508
Ethane, dichloro-	Air	mg	42.07697
Ethane, dichloro-	Water	mg	21.64462
Ethane, hexachloro-	Water	ng	480.8662
Ethane, hexafluoro-, HFC-116	Air	mg	111.3146
Ethanol	Air	g	9.54811
Ethene	Air	g	72.37836
Ethene	Water	g	9.99336
Ethene, chloro-	Air	g	3.354305
Ethene, trichloro-	Air	µg	955.299
Ethene, trichloro-	Water	mg	3.606496
Ethylene diamine	Air	µg	12.58508
Ethylene diamine	Water	µg	30.50928
Ethylene oxide	Air	mg	121.4612
Ethylene oxide	Water	µg	333.3076
Ethyne	Air	g	3.890536
Fatty acids as C	Water	g	33.28602
Feldspar, in ground	Raw	mg	3.844588
Fenpiclonil	Soil	mg	2.163147
Fluoride	Water	g	338.5426
Fluoride	Soil	g	3.131139
Fluorine	Air	g	4.339081
Fluorine, 4.5% in apatite, 1% in crude ore, in ground	Raw	g	73.20847
Fluorine, 4.5% in apatite, 3% in crude ore, in ground	Raw	g	32.20817
Fluorspar, 92%, in ground	Raw	kg	1.720655
Fluosilicic acid	Air	mg	115.2865
Fluosilicic acid	Water	mg	207.4885
Formaldehyde	Air	g	37.26526
Formaldehyde	Water	g	1.317592
Gas, mine, off-gas, process, coal mining/kg	Raw	kg	3.807674
Gas, mine, off-gas, process, coal mining/m3	Raw	m3	32.14368
Gas, natural, 35 MJ per m3, in ground	Raw	m3	97.12782
Gas, natural, 36.6 MJ per m3, in ground	Raw	m3	61.048
Gas, natural, 46.8 MJ per kg, in ground	Raw	kg	16.61251
Gas, natural, in ground	Raw	m3	3487.112
Gas, petroleum, 35 MJ per m3, in ground	Raw	m3	8.90704
Glutaraldehyde	Water	mg	90.81577
Glyphosate	Soil	mg	190.7249
Granite, in ground	Raw	g	1.824759

Substance	Compart -ment	Unit	Total
Gypsum, in ground	Raw	g	24.62867
Heat, waste	Air	MJ	303765.5
Heat, waste	Water	MJ	4959.813
Heat, waste	Soil	MJ	327.6923
Helium	Air	g	11.70684
Heptane	Air	g	14.27024
Hexane	Air	g	43.06114
Hydrocarbons, aliphatic, alkanes, cyclic	Air	mg	9.396533
Hydrocarbons, aliphatic, alkanes, unspecified	Air	g	400.5984
Hydrocarbons, aliphatic, alkanes, unspecified	Water	g	8.094324
Hydrocarbons, aliphatic, alkenes, unspecified	Air	g	3.296315
Hydrocarbons, aliphatic, alkenes, unspecified	Water	mg	79.59753
Hydrocarbons, aliphatic, unsaturated	Air	g	13.31416
Hydrocarbons, aliphatic, unsaturated	Water	mg	667.5495
Hydrocarbons, aromatic	Air	kg	1.403883
Hydrocarbons, aromatic	Water	g	38.05372
Hydrocarbons, chlorinated	Air	g	5.798304
Hydrocarbons, unspecified	Air	kg	2.836384
Hydrocarbons, unspecified	Water	g	87.11473
Hydrogen	Air	g	514.7517
Hydrogen	Water	mg	939.2
Hydrogen-3, Tritium	Air	Bq	1205593
Hydrogen-3, Tritium	Water	kBq	141381.6
Hydrogen chloride	Air	kg	1.030341
Hydrogen fluoride	Air	g	153.362
Hydrogen peroxide	Water	kg	6.000019
Hydrogen sulfide	Air	g	134.0963
Hydroxide	Water	mg	117.1394
Hypochlorite	Water	g	12.52249
Hypochlorous acid	Water	g	7.917881
Iodide	Water	g	6.475074
Iodine	Air	g	3.116256
Iodine-129	Air	Bq	264.4608
Iodine-129	Water	Bq	7146.928
Iodine-131	Air	Bq	9426.396
Iodine-131	Water	Bq	12.13531
Iodine-133	Air	Bq	6.848449
Iodine-133	Water	Bq	1.372399
Iodine-135	Air	Bq	9.986564
Iron	Air	g	78.03504
Iron	Water	kg	1.441221
Iron	Soil	g	441.6638
Iron-59	Air	µBq	783.8221
Iron-59	Water	mBq	71.69234
Iron ore, in ground	Raw	g	187.84
Iron, 46% in ore, 25% in crude ore, in ground	Raw	kg	2804.589
Iron, in ground	Raw	kg	6.815946
Iron, ion	Water	kg	18.50267
Isocyanic acid	Air	mg	76.63284
Kaolinite, 24% in crude ore, in ground	Raw	g	120.9358
Kerosene	Air	mg	25.3944
Kieserite, 25% in crude ore, in ground	Raw	mg	453.3952
Krypton-85	Air	Bq	1.85E+09
Krypton-85m	Air	Bq	5532.536
Krypton-87	Air	Bq	2361.141
Krypton-88	Air	Bq	88517.52
Krypton-89	Air	Bq	1012.446
Lanthanum	Air	mg	16.98634
Lanthanum-140	Air	mBq	62.64057
Lanthanum-140	Water	mBq	466.5749
Lead	Air	g	23.9781
Lead	Water	g	254.1065
Lead	Soil	mg	113.6118
Lead-210	Air	Bq	1215.831
Lead-210	Water	Bq	1264.691

Substance	Compart -ment	Unit	Total	Substance	Compart -ment	Unit	Total
Lead, in ground	Raw	g	37.98036	Methane, dichloro-, HCC-30	Air	mg	6.199926
Limestone, in ground	Raw	kg	1.701263	Methane, dichloro-, HCC-30	Water	g	1.009018
Linuron	Soil	mg	11.44403	Methane, dichlorodifluoro-, CFC-12	Air	mg	213.7049
m-Xylene	Air	mg	91.74642	Methane, dichlorofluoro-, HCFC-21	Air	mg	11.8728
Magnesite, 60% in crude ore, in ground	Raw	kg	38.20483	Methane, fossil	Air	kg	36.44166
Magnesium	Air	g	39.83624	Methane, monochloro-, R-40	Air	ng	129.3859
Magnesium	Water	kg	7.663476	Methane, tetrachloro-, CFC-10	Air	mg	129.0454
Magnesium	Soil	g	33.03003	Methane, tetrachloro-, CFC-10	Water	µg	87.15699
Magnesium, 0.13% in water	Raw	mg	49.67739	Methane, tetrafluoro-, FC-14	Air	g	1.001834
Mancozeb	Soil	mg	69.89013	Methane, trichlorofluoro-, CFC-11	Air	mg	15.45114
Manganese	Air	g	8.415865	Methane, trifluoro-, HFC-23	Air	µg	3.20626
Manganese	Water	g	356.0513	Methanol	Air	g	33.44963
Manganese	Soil	g	3.685984	Methanol	Water	g	2.28411
Manganese-54	Air	mBq	21.66398	Metolachlor	Soil	mg	82.82851
Manganese-54	Water	Bq	1697.242	Metribuzin	Soil	mg	2.456446
Manganese, 35.7% in sedimentary deposit, 14.2% in crude ore, in ground	Raw	kg	43.00797	Mineral waste	Waste	g	131.488
Manganese, in ground	Raw	g	7.029207	Molybdenum	Air	mg	442.4564
Marl, in ground	Raw	kg	13.81329	Molybdenum	Water	g	9.73198
Mercury	Air	g	3.54732	Molybdenum	Soil	µg	565.9287
Mercury	Water	g	2.918447	Molybdenum-99	Water	mBq	160.4755
Mercury	Soil	µg	125.6217	Molybdenum, 0.010% in sulfide, Mo 8.2E-3% and Cu 1.83% in crude ore, in ground	Raw	g	28.92101
Metaldehyde	Soil	µg	73.58139	Molybdenum, 0.014% in sulfide, Mo 8.2E-3% and Cu 0.81% in crude ore, in ground	Raw	g	4.115507
Metallic ions, unspecified	Water	g	5.061138				
Metals, unspecified	Air	mg	66.59102				
Methane	Air	kg	4.389393				
Methane, biogenic	Air	g	82.41849				
Methane, bromochlorodifluoro-, Halon 1211	Air	mg	134.5812				
Methane, bromotrifluoro-, Halon 1301	Air	mg	82.85448				
Methane, chlorodifluoro-, HCFC-22	Air	mg	520.64				

Substance	Compartment	Unit	Total
Molybdenum, 0.025% in sulfide, Mo 8.2E-3% and Cu 0.39% in crude ore, in ground	Raw	g	15.10105
Molybdenum, 0.11% in sulfide, Mo 4.1E-2% and Cu 0.36% in crude ore, in ground	Raw	kg	30.42118
Molybdenum, in ground	Raw	µg	22.71236
Monoethanolamine	Air	mg	226.7399
N-Nitrodimethylamine	Air	µg	213.6972
Naphthalene	Air	µg	208.2061
Napropamide	Soil	µg	130.2168
Neptunium-237	Air	µBq	19.65405
Neptunium-237	Water	Bq	3.15656
Nickel	Air	g	21.72233
Nickel	Soil	mg	251.6234
Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore, in ground	Raw	g	6.208531
Nickel, 1.98% in silicates, 1.04% in crude ore, in ground	Raw	kg	164.2432
Nickel, in ground	Raw	g	30.102
Nickel, ion	Water	kg	1.224073
Niobium-95	Air	mBq	3.760358
Niobium-95	Water	Bq	2.590249
Nitrate	Air	mg	82.98259
Nitrate	Water	kg	2.349139
Nitrite	Water	g	2.857006
Nitrogen	Air	g	26.26466
Nitrogen	Water	g	63.64159
Nitrogen	Soil	mg	8.594264
Nitrogen oxides	Air	kg	65.70038
Nitrogen, organic bound	Water	g	205.3222
Nitrogen, total	Water	g	7.843355
Noble gases, radioactive, unspecified	Air	kBq	1511113
Occupation, water courses, artificial	Raw	m2a	7.874312
Oil, crude, 42 MJ per kg, in ground	Raw	kg	175.0197
Oil, crude, 42.6 MJ per kg, in ground	Raw	kg	130.1283
Oil, crude, 42.7 MJ per kg, in ground	Raw	kg	966.4368
Oil, crude, in ground	Raw	kg	1279.529
Oils, biogenic	Soil	g	8.929652
Oils, unspecified	Water	kg	5.887099
Oils, unspecified	Soil	kg	3.794516
Olivine, in ground	Raw	g	3.85945
Orbencarb	Soil	mg	13.25609
Organic substances, unspecified	Air	kg	2.649471
Organic substances, unspecified	Water	g	3.094074
Ozone	Air	g	48.39808
PAH, polycyclic aromatic hydrocarbons	Air	g	3.186426
PAH, polycyclic aromatic hydrocarbons	Water	g	4.808563
Palladium, in ground	Raw	µg	19.03558
Paraffins	Air	µg	49.95309
Paraffins	Water	µg	144.9687
Particulates, < 10 um	Air	g	692.3945
Particulates, < 10 um (mobile)	Air	g	13.69127
Particulates, < 10 um (stationary)	Air	g	549.7027
Particulates, < 2.5 um	Air	kg	8.231194
Particulates, > 10 um	Air	kg	18.84148
Particulates, > 10 um (process)	Air	kg	1.05779
Particulates, > 2.5 um, and < 10um	Air	kg	12.61676
Particulates, SPM	Air	g	281.76

Substance	Compartment	Unit	Total
Pd, Pd 2.0E-4%, Pt 4.8E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	Raw	mg	1.060535
Pd, Pd 7.3E-4%, Pt 2.5E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	Raw	mg	2.548772
Peat, in ground	Raw	g	52.86013
Pentane	Air	g	201.2264
Phenol	Air	g	3.614987
Phenol	Water	g	7.341032
Phenol, pentachloro-	Air	mg	56.35176
Phenols, unspecified	Water	mg	926.4377
Phosphate	Water	kg	2.429568
Phosphorus	Air	g	1.429899
Phosphorus	Water	g	41.46764
Phosphorus	Soil	g	3.232098
Phosphorus compounds, unspecified	Water	mg	5.723578
Phosphorus, 18% in apatite, 12% in crude ore, in ground	Raw	g	130.6927
Phosphorus, 18% in apatite, 4% in crude ore, in ground	Raw	g	292.8339
Phosphorus, total	Air	mg	516.7068
Phthalate, dioctyl-	Water	µg	1.936456
Phthalate, p-dibutyl-	Water	µg	20.78721
Phthalate, p-dimethyl-	Water	µg	130.8824
Pirimicarb	Soil	µg	71.39008
Platinum	Air	µg	9.540688
Platinum, in ground	Raw	µg	21.50018
Plutonium-238	Air	µBq	66.17629
Plutonium-241	Air	Bq	32.75675
Plutonium-241	Water	Bq	4883.734
Plutonium-alpha	Air	Bq	1.191219
Plutonium-alpha	Water	Bq	196.5405
Polonium-210	Water	Bq	1702.801
Potassium	Air	g	37.08925
Potassium	Water	g	304.5242
Potassium	Soil	g	17.99021
Potassium-40	Air	Bq	254.2935
Potassium-40	Water	Bq	642.8337
Potassium, ion	Water	kg	3.341365
Promethium-147	Air	Bq	10.12481
Propanal	Air	µg	259.8542
Propane	Air	g	236.1395
Propene	Air	g	15.21147
Propene	Water	g	14.95168
Propionic acid	Air	g	1.766162
Propylene oxide	Air	mg	38.12241
Propylene oxide	Water	mg	91.7321
Protactinium-234	Air	Bq	33.3629
Protactinium-234	Water	Bq	617.8315
Pt, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	Raw	µg	38.13499
Pt, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	Raw	µg	136.7083
Radioactive species, alpha emitters	Water	Bq	2.523059
Radioactive species, from fission and activation	Water	Bq	148.1175
Radioactive species, Nuclides, unspecified	Water	Bq	153207.6
Radioactive species, other beta emitters	Air	Bq	1466.561
Radioactive species, unspecified	Air	Bq	1428990
Radium-224	Water	Bq	3107.329
Radium-226	Air	Bq	1346.121
Radium-226	Water	Bq	1163125
Radium-228	Air	Bq	377.7345
Radon-220	Air	Bq	2617.677
Radon-222	Air	kBq	5526717
Rh, Rh 2.0E-5%, Pt	Raw	µg	24.19892

Substance	Compart-ment	Unit	Total
Rhenium, in crude ore, in ground	Raw	µg	35.41309
Rhenium, in ground	Raw	µg	19.98954
Rhodium, in ground	Raw	µg	20.21859
Rubidium	Water	mg	571.636
Ruthenium	Water	mg	66.40942
Ruthenium-103	Air	µBq	235.5344
Ruthenium-103	Water	mBq	112.8238
Ruthenium-106	Air	Bq	119.1155
Ruthenium-106	Water	Bq	11911.55
Rutile, in ground	Raw	mg	2.847257
Salts, unspecified	Water	kg	2.528011
Sand, unspecified, in ground	Raw	kg	3.37128
Scandium	Air	mg	15.46447
Scandium	Water	g	1.162282
Selenium	Air	mg	999.606
Selenium	Water	g	6.527265
Shale, in ground	Raw	g	35.48631
Silicon	Air	g	263.2811
Silicon	Water	kg	261.8623
Silicon	Soil	g	12.64651
Silicon tetrafluoride	Air	mg	2.213953
Silver	Air	µg	13.18643
Silver	Water	mg	4.584341
Silver	Soil	mg	6.659462
Silver-110	Air	mBq	20.47786
Silver-110	Water	Bq	382.493
Silver, 0.01% in crude ore, in ground	Raw	mg	6.96347
Silver, in ground	Raw	mg	409.6548
Silver, ion	Water	mg	462.6252
Sodium	Air	g	32.13414
Sodium	Soil	g	75.3968
Sodium-24	Water	Bq	8.67209
Sodium chlorate	Air	mg	23.16014
Sodium chloride, in ground	Raw	kg	168.29
Sodium dichromate	Air	g	23.81324
Sodium formate	Air	mg	6.088423
Sodium formate	Water	mg	14.62707
Sodium sulphate, various forms	Raw	g	536.6387
Solids, inorganic	Water	kg	7.970461
Solved solids	Water	kg	27.13136
Solved substances	Water	g	384.565
Soot	Air	g	224
Stibnite, in ground	Raw	µg	94.95052
Strontium	Air	g	2.163501
Strontium	Water	g	464.6105
Strontium	Soil	mg	374.9422
Strontium-89	Air	mBq	35.78911
Strontium-89	Water	Bq	4.518675
Strontium-90	Air	Bq	19.66082
Strontium-90	Water	Bq	262007.9
Styrene	Air	µg	714.042
Sulfate	Air	kg	1.174941
Sulfate	Water	kg	73.59671
Sulfide	Water	mg	923.2918
Sulfite	Water	g	12.01515
Sulfur	Water	g	10.41348
Sulfur	Soil	g	29.52397
Sulfur dioxide	Air	kg	42.47495
Sulfur hexafluoride	Air	mg	744.2563
Sulfur oxides	Air	kg	15.49737
Sulfur trioxide	Water	mg	817.7574
Sulfur, in ground	Raw	g	60.11601
Sulfuric acid	Water	mg	765.673
Suspended solids, unspecified	Water	kg	15.01076
Sylvite, 25 % in sylvinite, in ground	Raw	g	187.2348
t-Butyl methyl ether	Air	mg	38.49447
t-Butyl methyl ether	Water	mg	119.8838
Tebutam	Soil	µg	308.5959
Technetium-99	Air	µBq	833.8082
Technetium-99	Water	Bq	1250.712
Technetium-99m	Water	Bq	3.436921
Teflubenzuron	Soil	µg	163.5813
Tellurium-123m	Air	mBq	89.99561
Tellurium-123m	Water	Bq	4.218582
Tellurium-132	Water	mBq	12.55518
Thallium	Air	mg	17.7585
Thallium	Water	mg	112.9205
Thorium	Air	mg	23.63966
Thorium-228	Air	Bq	75.98147
Thorium-228	Water	Bq	12439.53

Substance	Compart -ment	Unit	Total
Thorium-230	Water	Bq	88690.47
Thorium-232	Air	Bq	73.85818
Thorium-232	Water	Bq	101.0831
Thorium-234	Air	Bq	33.36706
Thorium-234	Water	Bq	619.7301
Tin	Air	g	1.742002
Tin	Soil	µg	977.7376
Tin, 79% in cassiterite, 0.1% in crude ore, in ground	Raw	g	10.50464
Tin, in ground	Raw	mg	227.586
Tin, ion	Water	g	42.68791
TiO2, 45-60% in Ilmenite, in ground	Raw	kg	1.213725
Titanium	Air	g	4.038263
Titanium	Soil	mg	124.8892
Titanium, ion	Water	kg	1.198245
TOC, Total Organic Carbon	Water	kg	31.31826
Toluene	Air	g	38.87735
Toluene	Water	g	7.634404
Tributyltin	Water	mg	22.29989
Tributyltin compounds	Water	mg	290.2995
Triethylene glycol	Water	g	3.006718
Tungsten	Water	g	1.156005
Ulexite, in ground	Raw	mg	598.0731
Undissolved substances	Water	g	560.8188
Uranium	Air	mg	25.90298
Uranium-234	Water	Bq	771.5248
Uranium-235	Air	Bq	19.07477
Uranium-235	Water	Bq	1225.786
Uranium-238	Air	Bq	595.0755
Uranium-238	Water	Bq	2514.996
Uranium alpha	Air	Bq	1597.436
Uranium alpha	Water	Bq	37303.6
Uranium, 2291 GJ per kg, in ground	Raw	mg	116.8156
Uranium, 560 GJ per kg, in ground	Raw	g	48.73852
Uranium, in ground	Raw	g	88.04857
Vanadium	Air	g	50.81324
Vanadium	Soil	mg	3.574727
Vermiculite, in ground	Raw	g	3.90706
VOC, volatile organic compounds	Air	kg	13.28
VOC, volatile organic compounds as C	Water	g	2.28111
VOC, volatile organic compounds, unspecified origin	Water	g	20.46288
Volume occupied, final repository for low-active radioactive waste	Raw	cm3	181.218
Volume occupied, final repository for radioactive waste	Raw	cm3	45.47186
Volume occupied, reservoir	Raw	m3y	183.2541
Volume occupied, underground deposit	Raw	l	4.297114
Waste, solid	Waste	kg	15.26405
water	Air	kg	2.83083
Water, cooling, unspecified natural origin/m3	Raw	m3	1967.105
Water, lake	Raw	m3	4.101295
Water, salt, ocean	Raw	m3	7.716365
Water, salt, sole	Raw	l	687.8833
Water, turbine use, unspecified natural origin	Raw	m3	84301.88
Water, unspecified natural origin/kg	Raw	kg	101954.5
Water, unspecified natural origin/m3	Raw	m3	92.18922
Water, well, in ground	Raw	m3	23.32385
Wood and wood waste, 9.5 MJ per kg	Raw	g	141.5187
Wood, dry matter	Raw	kg	6.988763
Wood, hard, standing	Raw	l	47.48475
Wood, soft, standing	Raw	l	249.2697
Wood, unspecified	Raw	cm3	8.936381

Substance	Compart-ment	Unit	Total	Substance	Compart-ment	Unit	Total
Xenon-133	Air	Bq	1527031	Zinc	Air	g	66.50914
Xenon-133m	Air	Bq	1558.357	Zinc	Soil	g	4.355994
Xenon-135	Air	Bq	308350	Zinc-65	Air	mBq	93.75808
Xenon-135m	Air	Bq	70590.39	Zinc-65	Water	Bq	30.71628
Xenon-137	Air	Bq	1455.474	Zinc, in ground	Raw	mg	198.7035
Xenon-138	Air	Bq	14112.99	Zinc, ion	Water	g	838.3893
Xylene	Air	g	52.10704	Zirconium	Air	mg	49.8403
Xylene	Water	g	6.315903	Zirconium-95	Air	mBq	7.132802
Yttrium-90	Water	mBq	28.45392	Zirconium-95	Water	Bq	101.4523

A.4 IN-SITU S/S

Table A.4 Environmental interventions – In-situ S/S

Substance	Compart-ment	Unit	Total	Substance	Compart-ment	Unit	Total
Aluminium, 24% in bauxite, 11% in crude ore, in ground	Raw	kg	105.9293	Coal, 26.4 MJ per kg, in ground	Raw	kg	1956.414
Anhydrite, in ground	Raw	g	1.699139	Coal, 29.3 MJ per kg, in ground	Raw	g	957.984
Barite, 15% in crude ore, in ground	Raw	kg	102.8394	Coal, brown, in ground	Raw	kg	5205.954
Basalt, in ground	Raw	kg	109.4332	Coal, hard, unspecified, in ground	Raw	kg	53545.67
Bauxite, in ground	Raw	kg	1.12704	Cobalt, in ground	Raw	mg	193.2332
Borax, in ground	Raw	g	1.508389	Colemanite, in ground	Raw	g	36.72939
Calcite, in ground	Raw	kg	1081041	Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	Raw	kg	1.285286
Coal, brown in ground	Raw	kg	2125.005	Copper, 1.18% in sulfide, Cu 0.39%	Raw	kg	7.124322
Chromium, 25.5 in chromite, 11.6% in crude ore, in ground	Raw	kg	26.63343				
Chrysotile, in ground	Raw	mg	884.3689				
Cinnabar, in ground	Raw	mg	81.18298				
Clay, bentonite	Raw	kg	400021.6				

Substance	Compart-ment	Unit	Total
Dolomite, in ground	Raw	kg	2.216181
Energy, gross calorific value, in biomass	Raw	MJ	23753.9
Energy, kinetic, flow, in wind	Raw	MJ	4001.444
Energy, potential, stock, in barrage water	Raw	MJ	251230.5
Energy, solar	Raw	MJ	265.4486
Energy, unspecified	Raw	MJ	9551.664
Feldspar, in ground	Raw	mg	17.49542
Fluorine, 4.5% in apatite, 1% in crude ore, in ground	Raw	g	74.6461
Fluorine, 4.5% in apatite, 3% in crude ore, in ground	Raw	g	33.75957
Fluorspar, 92%, in ground	Raw	kg	2.995414
Gas, mine, off-gas, process, coal mining/m3	Raw	m3	849.8616
Gas, natural, 36.6 MJ per m3, in ground	Raw	m3	183.144
Gas, natural, 46.8 MJ per kg, in ground	Raw	ton	7.976148
Gas, natural, in ground	Raw	m3	5609.708
Granite, in ground	Raw	g	5.462804
Gravel, in ground	Raw	kg	20601.81
Gypsum, in ground	Raw	g	9.313815
Iron ore, in ground	Raw	g	563.52
Iron, 46% in ore, 25% in crude ore, in ground	Raw	kg	951.4907
Kaolinite, 24% in crude ore, in ground	Raw	g	959.215
Kieserite, 25% in crude ore, in ground	Raw	g	3.714463
Lead, 5%, in sulfide, Pb 2.97% and Zn 5.34% in crude ore, in ground	Raw	kg	9.05018

Substance	Compart-ment	Unit	Total
Limestone	Raw	kg	113.472
Magnesium, 0.13% in water	Raw	mg	527.8301
Manganese, 35.7% in sedimentary deposit, 14.2% in crude ore, in ground	Raw	kg	5.517967
Molybdenum, 0.010% in sulfide, Mo 8.2E-3% and Cu 1.83% in crude ore, in ground	Raw	g	174.2021
Molybdenum, 0.014% in sulfide, Mo 8.2E-3% and Cu 0.81% in crude ore, in ground	Raw	g	24.78924
Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36% in crude ore, in ground	Raw	kg	1.931979
Molybdenum, 0.025% in sulfide, Mo 8.2E-3% and Cu 0.39% in crude ore, in ground	Raw	g	90.95928
Molybdenum, 0.11% in sulfide, Mo 4.1E-2% and Cu 0.36% in crude ore, in ground	Raw	kg	3.899167
Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore, in ground	Raw	g	336.233
Nickel, 1.98% in silicates, 1.04% in crude ore, in ground	Raw	kg	60.50383
Oil, crude, 42 MJ per kg, in ground	Raw	ton	114.9318
Oil, crude, 42.7 MJ per kg, in ground	Raw	kg	2899.31
Oil, crude, in ground	Raw	kg	37658.24
Olivine, in ground	Raw	mg	622.825

Substance	Compartment	Unit	Total
Pd, Pd 7.3E-4%, Pt 2.5E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	Raw	mg	97.00497
Peat, in ground	Raw	g	282.1023
Phosphorus, 18% in apatite, 4% in crude ore, in ground	Raw	g	298.5844
Pt, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	Raw	mg	1.254964
Pt, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	Raw	mg	4.498862
Rh, Rh 2.0E-5%, Pt 2.5E-4%, Pd 7.3E-4%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	Raw	µg	920.1448
Rh, Rh 2.4E-5%, Pt 4.8E-4%, Pd 2.0E-4%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	Raw	mg	2.882011
Rhenium, in crude ore, in ground	Raw	mg	3.616412
Rutile, in ground	Raw	µg	998.278
Sand, unspecified, in ground	Raw	g	55.48315
Shale, in ground	Raw	g	4.809224
Silver, 0.01% in crude ore, in ground	Raw	mg	125.7066
Sodium chloride, in ground	Raw	kg	81.33357
Sodium sulphate, various forms, in ground	Raw	g	593.481
Stibnite, in ground	Raw	µg	579.5039
Sulfur, in ground	Raw	g	85.36559
Talc, in ground	Raw	g	100.5844
Tin, 79% in cassiterite, 0.1% in crude ore, in ground	Raw	g	216.9115
TiO2, 45-60% in Ilmenite, in ground	Raw	kg	2.398212
Transformation, from arable	Raw	cm2	785.6018
Transformation, from arable, non-irrigated	Raw	dm2	864.9714
Ulexite, in ground	Raw	g	1.95802
Uranium, in ground	Raw	kg	1.098481
Vermiculite, in ground	Raw	g	64.30087
Volume occupied, final repository for low-active radioactive waste	Raw	l	2.264903
Volume occupied, final repository for radioactive waste	Raw	cm3	505.7269
Volume occupied, reservoir	Raw	m3y	3357.713
Volume occupied, underground deposit	Raw	cm3	975.292
Water, cooling, unspecified natural origin/m3	Raw	m3	666.5715
Water, lake	Raw	m3	67.4917
Water, river	Raw	m3	590.6241
Water, salt, ocean	Raw	m3	47.35109
Water, salt, sole	Raw	m3	20.56113
Water, turbine use, unspecified natural origin	Raw	m3	1594900
Water, unspecified natural origin/kg	Raw	kg	154.968
Water, unspecified natural origin/m3	Raw	m3	1632.155
Water, well, in ground	Raw	m3	254.4985
Wood and wood waste, 9.5 MJ per kg	Raw	kg	82.16938
Wood, hard, standing	Raw	l	563.0552

Substance	Compartment	Unit	Total
Wood, unspecified, standing/m3	Raw	cm3	41.33072
Zinc 9%, in sulfide, Zn 5.34% and Pb 2.97% in crude ore, in ground	Raw	kg	10.077
Acenaphthene	Air	µg	26.77255
Acetaldehyde	Air	g	6.694996
Acetic acid	Air	g	47.19083
Acetone	Air	g	8.983988
Acrolein	Air	mg	116.8596
Actinides, radioactive, unspecified	Air	mBq	16.38459
Aerosols, radioactive, unspecified	Air	Bq	281.5789
Aluminum	Air	kg	14.42865
Ammonia	Air	kg	29.25555
Ammonium carbonate	Air	mg	28.06865
Antimony	Air	g	3.09282
Antimony-124	Air	mBq	28.9654
Antimony-125	Air	mBq	302.2782
Argon-41	Air	Bq	121064.2
Arsenic	Air	g	18.68877
Barium	Air	g	2.25432
Barium-140	Air	Bq	19.66275
Benzaldehyde	Air	mg	22.29808
Benzene	Air	kg	1.567482
Benzene, ethyl-	Air	g	61.68926
Benzene, hexachloro-	Air	mg	9.919333
Benzene, pentachloro-	Air	mg	2.496321
Benzo(a)pyrene	Air	mg	692.6713
Beryllium	Air	g	2.807729
Boron	Air	g	128.9747
Bromine	Air	g	9.415192
Butadiene	Air	µg	7.303268
Butane	Air	kg	2.384753
Butene	Air	g	52.94059
Cadmium	Air	g	11.29845
Calcium	Air	g	39.19074
Carbon-14	Air	Bq	2100292
Carbon dioxide, biogenic	Air	kg	15401.06
Carbon dioxide, fossil	Air	kg	1197682
Carbon disulfide	Air	g	227.0956
Carbon monoxide	Air	kg	3034.323
Carbon monoxide, biogenic	Air	kg	2.864642
Carbon monoxide, fossil	Air	kg	669.4051
Cerium-141	Air	Bq	4.766695
Cesium-134	Air	mBq	228.2941
Cesium-137	Air	Bq	4.046911
Chlorine	Air	g	39.77895
Chloroform	Air	mg	36.31662
Chromium	Air	g	73.31667
Chromium-51	Air	mBq	305.449
Chromium VI	Air	g	2.236264
Cobalt	Air	g	8.380051
Cobalt-58	Air	mBq	425.3503
Cobalt-60	Air	Bq	3.757575
Cumene	Air	g	14.42069
Cyanide	Air	g	2.411478
Dinitrogen monoxide	Air	kg	4.350519
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	Air	µg	885.8775
Ethane	Air	kg	1.121872
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	Air	g	7.700277
Ethane, 1,2-dichloro-	Air	g	2.298153
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	Air	mg	552.9017
Ethane, hexafluoro-, HFC-116	Air	mg	704.4162
Ethanol	Air	g	12.48999
Ethene	Air	g	182.571
Ethene, chloro-	Air	g	4.746744
Ethene, tetrachloro-	Air	mg	69.22695
Ethene, trichloro-	Air	mg	66.21708
Ethylene diamine	Air	µg	96.80508

Substance	Compart-ment	Unit	Total
Ethyne	Air	g	4.039788
Fluorine	Air	g	1.453605
Fluosilicic acid	Air	mg	823.3782
Formaldehyde	Air	kg	31.91336
Heat, waste	Air	MJ	4562388
Helium	Air	g	289.2284
Heptane	Air	g	529.3723
Hexane	Air	kg	1.177841
Hydrocarbons, aliphatic, alkanes, cyclic	Air	mg	59.30332
Hydrocarbons, aliphatic, alkanes, unspecified	Air	g	508.0488
Hydrocarbons, aliphatic, unsaturated	Air	g	79.79588
Hydrocarbons, aromatic	Air	g	99.69912
Hydrocarbons, chlorinated	Air	g	2.043728
Hydrocarbons, unspecified	Air	kg	8.509152
Hydrogen	Air	g	179.2981
Hydrogen-3, Tritium	Air	Bq	8189232
Hydrogen fluoride	Air	g	273.6139
Hydrogen sulfide	Air	g	89.77572
Iodine	Air	g	4.649122
Iodine-129	Air	Bq	1559.277
Iodine-131	Air	Bq	44296.95
Iodine-133	Air	Bq	23.51053
Iron	Air	g	47.03536
Isocyanic acid	Air	mg	592.1315
Kerosene	Air	g	1.504934
Krypton-85	Air	Bq	392526.1
Krypton-85m	Air	Bq	288403.8
Krypton-87	Air	Bq	66981.84
Krypton-88	Air	Bq	86359.94
Krypton-89	Air	Bq	35680.32
Lanthanum-140	Air	Bq	1.680498
Lead	Air	g	109.5977
Lead-210	Air	Bq	3371.975
m-Xylene	Air	mg	451.0679
Magnesium	Air	g	29.56695
Manganese	Air	g	6.633315
Mercury	Air	g	32.41285
Metals, unspecified	Air	g	37.62334
Methane	Air	kg	60.94981
Methane, biogenic	Air	g	509.9114
Methane, bromochlorodifluoro-, Halon 1211	Air	mg	120.955
Methane, bromotrifluoro-, Halon 1301	Air	g	1.88181
Methane, chlorodifluoro-, HCFC-22	Air	mg	621.9746
Methane, dichloro-, HCC-30	Air	mg	317.136
Methane, dichlorodifluoro-, CFC-12	Air	µg	879.6368
Methane, dichlorofluoro-, HCFC-21	Air	ng	166.9262
Methane, fossil	Air	kg	659.4497
Methane, monochloro-, R-40	Air	ng	770.4656
Methane, tetrachloro-, CFC-10	Air	mg	315.8236
Methane, tetrafluoro-, FC-14	Air	g	6.339746
Methane, trifluoro-, HFC-23	Air	µg	53.11288
Molybdenum	Air	mg	781.6389
Monoethanolamine	Air	g	2.106165
N-Nitrodimethylamine	Air	mg	14.89884
Naphthalene	Air	mg	105.3454
Nickel	Air	g	71.91111
Niobium-95	Air	mBq	18.56886
Nitrate	Air	mg	648.478
Nitrogen oxides	Air	kg	5803.736
NMVOC, non-methane volatile organic compounds, unspecified origin	Air	kg	1500.923
Noble gases,	Air	Bq	1.50E+10

Substance	Compart-ment	Unit	Total
Ozone	Air	g	492.68
PAH, polycyclic aromatic hydrocarbons	Air	g	13.856
Paraffins	Air	µg	470.7667
Particulates, < 10 um	Air	kg	465.2531
Particulates, < 2.5 um	Air	kg	54.67534
Particulates, > 10 um	Air	kg	196.0133
Particulates, > 2.5 um, and < 10um	Air	kg	69.23615
Particulates, SPM	Air	g	845.28
Particulates, unspecified	Air	kg	24.9819
Pentane	Air	kg	3.08182
Phenol	Air	g	24.70247
Phenol, pentachloro-	Air	mg	223.6854
Phosphorus	Air	g	1.901606
Platinum	Air	µg	263.8523
Plutonium-238	Air	µBq	212.7107
Plutonium-alpha	Air	µBq	487.6121
Polonium-210	Air	Bq	5508.648
Polychlorinated biphenyls	Air	mg	15.2784
Potassium	Air	g	98.40248
Potassium-40	Air	Bq	463.4547
Propanal	Air	mg	22.29808
Propane	Air	kg	2.439238
Propene	Air	g	117.6313
Propionic acid	Air	g	1.107146
Protactinium-234	Air	Bq	268.7634
Radioactive species, other beta emitters	Air	Bq	8950.194
Radioactive species, unspecified	Air	kBq	106833.5
Radium-226	Air	Bq	9508.455
Radium-228	Air	Bq	553.6715
Radon-220	Air	Bq	6.513283
Radon-222	Air	Bq	3.57E+10
Ruthenium-103	Air	mBq	4.079699
Scandium	Air	mg	9.738104
Selenium	Air	g	4.845865
Silicon	Air	g	124.1205
Silicon tetrafluoride	Air	mg	2.25742

Substance	Compart-ment	Unit	Total
Silver-110	Air	mBq	40.43294
Sodium	Air	g	46.78827
Sodium chlorate	Air	mg	48.53807
Sodium dichromate	Air	mg	146.1077
Sodium formate	Air	mg	5.055045
Soot	Air	g	672
Strontium	Air	g	2.389912
Styrene	Air	mg	2.844178
Sulfate	Air	g	239.1086
Sulfur dioxide	Air	kg	440.9983
Sulfur hexafluoride	Air	g	5.204347
Sulfur oxides	Air	kg	910.3792
t-Butyl methyl ether	Air	g	20.54969
Thallium	Air	g	11.75884
Thorium	Air	mg	13.90655
Thorium-228	Air	Bq	106.0938
Thorium-230	Air	Bq	999.8057
Thorium-232	Air	Bq	133.2225
Thorium-234	Air	Bq	268.8195
Tin	Air	g	9.781935
Titanium	Air	g	2.836492
Toluene	Air	kg	1.60861
Uranium	Air	mg	17.25448
Uranium-234	Air	Bq	3139.74
Uranium-235	Air	Bq	152.2993
Uranium-238	Air	Bq	3456.327
Uranium alpha	Air	Bq	14668.73
Vanadium	Air	g	80.83834
VOC, volatile organic compounds	Air	kg	39.84
water	Air	kg	22.04729
Xenon-131m	Air	Bq	347444.2
Xenon-133	Air	Bq	12603690
Xenon-133m	Air	Bq	15035.54
Xenon-135m	Air	Bq	3170285
Xenon-137	Air	Bq	97675.15
Xenon-138	Air	Bq	733766.3
Xylene	Air	kg	1.385374
Zinc	Air	g	172.9175
Zinc-65	Air	mBq	781.0616
Zirconium	Air	mg	18.92734
Zirconium-95	Air	mBq	763.4581
Acenaphthene	Water	mg	11.57146
Acenaphthylene	Water	µg	723.6815

Substance	Compartment	Unit	Total
Acidity, unspecified	Water	g	11.19165
Actinides, radioactive, unspecified	Water	Bq	2532.699
Aluminum	Water	kg	19.21558
Ammonia	Water	g	238.8667
Ammonium, ion	Water	g	316.0197
Antimony	Water	g	9.795409
Antimony-122	Water	Bq	11.67776
Antimony-124	Water	Bq	801.7283
Antimony-125	Water	Bq	740.2149
AOX, Adsorbable Organic Halogen as Cl	Water	g	1.257438
Arsenic, ion	Water	g	24.78932
Barite	Water	kg	3.217727
Barium	Water	kg	1.92961
Barium-140	Water	Bq	51.15478
Benzene	Water	g	143.6146
Benzene, ethyl-	Water	g	44.6535
Beryllium	Water	g	1.455828
BOD5, Biological Oxygen Demand	Water	kg	228.0068
Boron	Water	g	784.743
Bromate	Water	g	4.675654
Bromine	Water	kg	1.372185
Butene	Water	mg	8.016169
Cadmium, ion	Water	g	30.77401
Calcium, ion	Water	kg	136.5166
Carbonate	Water	g	120.1278
Carboxylic acids, unspecified	Water	kg	7.375705
Cerium-141	Water	Bq	20.45252
Cerium-144	Water	Bq	6.226415
Cesium	Water	g	1.860364
Cesium-134	Water	Bq	301.3719
Cesium-136	Water	Bq	3.629922
Cesium-137	Water	Bq	296681.3
Chlorate	Water	g	46.18591
Chlorinated solvents, unspecified	Water	g	1.41358
Chlorine	Water	g	41.06047
Chloroform	Water	ng	166.9262
Chromate	Water	g	1.474835
Chromium-51	Water	Bq	3814.92
Chromium VI	Water	g	197.3878
Chromium, ion	Water	g	10.35835
Cobalt	Water	g	100.5989
Cobalt-57	Water	Bq	115.2274
Cobalt-58	Water	Bq	16879.86
Cobalt-60	Water	Bq	14941.86
COD, Chemical Oxygen Demand	Water	kg	317.9004
Copper, ion	Water	g	357.4111
Cumene	Water	g	34.65271
Cyanide	Water	g	110.3758
Dichromate	Water	mg	539.9524
DOC, Dissolved Organic Carbon	Water	kg	81.32451
Ethane, 1,2-dichloro-	Water	mg	156.2162
Ethene	Water	g	4.566682
Ethene, chloro-	Water	mg	104.2789
Ethylene diamine	Water	µg	234.679
Ethylene oxide	Water	mg	3.096062
Fluoride	Water	g	495.2155
Fluosilicic acid	Water	g	1.481916
Formaldehyde	Water	g	2.579756
Glutaraldehyde	Water	mg	397.2503
Heat, waste	Water	MJ	24529.6
Hydrocarbons, aliphatic, alkanes, unspecified	Water	g	241.8473
Hydrocarbons, aliphatic, unsaturated	Water	g	22.32437
Hydrocarbons, aromatic	Water	g	989.0582
Hydrocarbons, unspecified	Water	g	160.8193
Hydrogen	Water	g	2.8176
Hydrogen-3, Tritium	Water	Bq	6.72E+08
Hydrogen peroxide	Water	mg	196.0804
Hydrogen sulfide	Water	g	28.41191
Hydroxide	Water	g	1.297901
Hypochlorite	Water	g	8.776591
Iodide	Water	g	186.6924
Iodine-133	Water	Bq	32.11383
Iron	Water	g	285.9374
Iron-59	Water	Bq	8.828779

Substance	Compartment	Unit	Total
Lanthanum-140	Water	Bq	54.48407
Lead	Water	g	107.6114
Lead-210	Water	Bq	2042.541
Magnesium	Water	kg	19.12412
Manganese	Water	g	581.9528
Manganese-54	Water	Bq	1015.911
Mercury	Water	g	1.4063
Metallic ions, unspecified	Water	kg	2.711698
Methane, dichloro-, HCC-30	Water	g	15.72295
Methanol	Water	g	2.226286
Molybdenum	Water	g	21.17766
Molybdenum-99	Water	Bq	18.78494
Nickel, ion	Water	g	493.442
Niobium-95	Water	Bq	69.46923
Nitrate	Water	kg	1.048203
Nitrite	Water	g	6.428429
Nitrogen	Water	g	247.4571
Nitrogen, organic bound	Water	g	396.7081
Oils, unspecified	Water	kg	78.66533
Organic substances, unspecified	Water	kg	1.279194
PAH, polycyclic aromatic hydrocarbons	Water	g	11.47325
Paraffins	Water	mg	1.366211
Phenol	Water	g	177.0328
Phosphate	Water	kg	1.088428
Phosphorus	Water	g	13.0789
Polonium-210	Water	Bq	2494.897
Potassium-40	Water	Bq	1588.562
Potassium, ion	Water	kg	10.79457
Propene	Water	g	13.49248
Propylene oxide	Water	mg	901.9694
Protactinium-234	Water	Bq	4977.1
Radioactive species, alpha emitters	Water	Bq	3.501732
Radioactive species, Nuclides, unspecified	Water	Bq	1518581
Radium-224	Water	Bq	93018.19
Radium-226	Water	Bq	3246285
Radium-228	Water	Bq	186036.4
Scandium	Water	g	2.627046
Selenium	Water	g	4.693698
Silicon	Water	kg	180.9711
Silver-110	Water	Bq	14603.28
Silver, ion	Water	g	2.084372
Sodium-24	Water	Bq	142.1318
Sodium formate	Water	mg	12.14444
Sodium, ion	Water	kg	584.1175
Solids, inorganic	Water	kg	19.53751
Solved solids	Water	kg	538.0819
Strontium	Water	kg	11.55876
Strontium-89	Water	Bq	318.655
Strontium-90	Water	Bq	1219553
Sulfate	Water	kg	146.6651
Sulfide	Water	g	3.694163
Sulfite	Water	g	24.67131
Sulfur	Water	g	164.0968
Sulfuric acid	Water	g	103.8404
Suspended solids, unspecified	Water	kg	27.06767
t-Butyl methyl ether	Water	g	2.072151
Technetium-99m	Water	Bq	431.7227
Tellurium-123m	Water	Bq	47.61207
Tellurium-132	Water	Bq	1.087685
Thallium	Water	mg	238.8504
Thorium-228	Water	Bq	372083.3
Thorium-230	Water	Bq	679076.7
Thorium-232	Water	Bq	276.7951
Thorium-234	Water	Bq	4977.7
Tin, ion	Water	g	21.18419
Titanium, ion	Water	g	874.3509
TOC, Total Organic Carbon	Water	kg	81.64276
Toluene	Water	g	228.4359
Tributyltin compounds	Water	g	1.998066
Triethylene glycol	Water	g	1.235909
Tungsten	Water	g	3.091628
Uranium-234	Water	Bq	5972.52
Uranium-235	Water	Bq	9854.658
Uranium-238	Water	Bq	16050.76
Uranium alpha	Water	Bq	286737.7
Vanadium, ion	Water	g	95.21757
VOC	Water	g	663.011

Substance	Compart -ment	Unit	Total	Substance	Compart -ment	Unit	Total
Zinc-65	Water	Bq	1926.986	Heat, waste	Soil	MJ	2260.568
Zinc, ion	Water	g	787.0663	Iron	Soil	kg	3.470359
Mineral waste	Waste	g	394.464	Lead	Soil	mg	421.7381
Slags	Waste	g	140.88	Magnesium	Soil	g	513.1078
Waste, solid	Waste	kg	2001.562	Mancozeb	Soil	mg	480.5468
Aclonifen	Soil	mg	13.68242	Manganese	Soil	g	34.40278
Aluminum	Soil	g	633.6044	Metolachlor	Soil	mg	766.2906
Antimony	Soil	µg	45.41375	Metribuzin	Soil	mg	16.8899
Arsenic	Soil	mg	251.9337	Molybdenum	Soil	mg	2.515795
Atrazine	Soil	µg	739.936	Napropamide	Soil	mg	1.104975
Barium	Soil	g	310.5479	Nickel	Soil	mg	655.1712
Bentazone	Soil	mg	6.968236	Oils, biogenic	Soil	g	77.72302
Boron	Soil	g	9.883695	Oils, unspecified	Soil	kg	58.09093
Cadmium	Soil	mg	79.80806	Orbencarb	Soil	mg	91.14547
Calcium	Soil	kg	2.629291	Phosphorus	Soil	g	35.69712
Carbetamide	Soil	mg	2.8307	Pirimicarb	Soil	µg	660.5307
Carbon	Soil	kg	1.903967	Potassium	Soil	g	243.1977
Chloride	Soil	kg	8.995306	Silicon	Soil	g	106.0101
Chlorothalonil	Soil	mg	369.1128	Silver	Soil	mg	1.828347
Chromium	Soil	g	3.946349	Sodium	Soil	kg	1.260997
Chromium VI	Soil	g	20.70349	Strontium	Soil	g	6.280828
Cobalt	Soil	mg	9.817182	Sulfur	Soil	g	379.4808
Copper	Soil	g	14.32225	Tebutam	Soil	mg	2.61864
Cypermethrin	Soil	µg	72.05045	Teflubenzuron	Soil	mg	1.124744
Dinoseb	Soil	mg	100.3234	Tin	Soil	mg	3.286072
Fenpiclonil	Soil	mg	14.99444	Titanium	Soil	mg	653.9978
Fluoride	Soil	g	45.07049	Vanadium	Soil	mg	18.7195
Glyphosate	Soil	g	1.283573	Zinc	Soil	g	67.63829

A.5 EX-SITU S/S

Table A.5 Environmental interventions – Ex-situ S/S

Substance	Compartment	Unit	Total	Substance	Compartment	Unit	Total
Acenaphthene	Air	µg	26.77245	Antimony-124	Air	mBq	28.96539
Acenaphthene	Water	mg	11.57135	Antimony-124	Water	Bq	801.7279
Acenaphthylene	Water	µg	723.6745	Antimony-125	Water	Bq	740.2146
Acetaldehyde	Air	g	6.694974	AOX, Adsorbable Organic Halogen as Cl	Water	g	1.257423
Acetic acid	Air	g	47.19056	Argon-41	Air	Bq	121064
Acetic acid	Water	g	2.325055	Arsenic	Air	g	41.42345
Acetone	Air	g	8.983961	Arsenic	Soil	mg	251.9303
Acidity, unspecified	Water	g	13.57561	Arsenic, ion	Water	g	24.78902
Aclonifen	Soil	mg	13.68241	Atrazine	Soil	µg	739.9357
Acrolein	Air	g	1.541223	Barite	Water	kg	3.217659
Actinides, radioactive, unspecified	Air	mBq	16.38458	Barite, 15% in crude ore, in ground	Raw	kg	102.838
Actinides, radioactive, unspecified	Water	Bq	2532.697	Barium	Air	g	2.254312
Aerosols, radioactive, unspecified	Air	Bq	281.5785	Barium	Water	kg	1.929593
Aldehydes, unspecified	Air	kg	1746.691	Barium	Soil	g	310.5437
Aluminium, 24% in bauxite, 11% in crude ore, in ground	Raw	kg	105.9293	Barium-140	Air	Bq	19.66275
Aluminum	Air	kg	14.42864	Barium-140	Water	Bq	51.15478
Aluminum	Water	kg	19.21552	Basalt, in ground	Raw	kg	109.4332
Aluminum	Soil	g	633.5959	Bauxite, in ground	Raw	kg	1.4088
Ammonia	Air	kg	40.63099	Bentazone	Soil	mg	6.968231
Ammonia	Water	kg	4.223088	Benzaldehyde	Air	mg	22.29806
Ammonium carbonate	Air	mg	28.06862	Benzene	Air	kg	1.571864
Ammonium, ion	Water	g	316.018	Benzene	Water	g	143.6133
Anhydrite, in ground	Raw	g	1.699136	Benzene, ethyl-	Air	g	61.68888
Antimony	Air	g	13.91693	Benzene, ethyl-	Water	g	44.65306
Antimony	Water	g	9.795383	Benzene, hexachloro-	Air	mg	9.919099
Antimony	Soil	µg	45.41374	Benzene, pentachloro-	Air	mg	2.496321
				Benzo(a)pyrene	Air	mg	692.662
				Beryllium	Air	g	4.405689
				Beryllium	Water	g	1.455823
				BOD5, Biological Oxygen Demand	Water	kg	264.9273
				Borax, in ground	Raw	g	1.508388

Substance	Compart -ment	Unit	Total
Boron	Soil	g	9.883606
Bromate	Water	g	4.675633
Bromine	Air	g	9.415162
Butadiene			
Butane	Air	µg	7.303205
Butene	Air	kg	2.384735
Butene	Air	g	52.94021
Cadmium	Water	mg	8.016166
Cadmium	Air	g	45.41995
Cadmium, ion	Soil	mg	79.80799
Calcite, in ground	Water	g	400.8011
Calcium	Raw	kg	1081041
Calcium	Air	g	39.19063
Calcium, ion	Soil	kg	2.629257
Carbetamide	Water	kg	136.5433
Carbon	Soil	mg	2.830698
Carbon-14	Soil	kg	1.903941
Carbon dioxide	Air	Bq	2100291
Carbon dioxide, biogenic	Air	kg	12950.94
Carbon dioxide, fossil	Air	kg	17134.59
Carbon dioxide, in air	Air	ton	8422.051
Carbon disulfide	Raw	kg	2125.004
Carbon monoxide	Air	g	227.0936
Carbon monoxide, biogenic	Air	kg	63982.72
Carbon monoxide, fossil	Air	kg	2.864641
Carbonate	Air	kg	669.4014
Carboxylic acids, unspecified	Water	g	120.1278
Cerium-141	Water	kg	7.375626
Cerium-141	Air	Bq	4.766695
Cerium-144	Water	Bq	20.45252
Cesium	Water	Bq	6.226415
Cesium-134	Water	g	1.860346
Cesium-134	Air	mBq	228.294
Cesium-136	Water	Bq	301.3716
Cesium-137	Water	Bq	3.629922
Cesium-137	Air	Bq	4.046911
Chlorate	Water	Bq	296681
Chloride	Water	g	46.18573

Substance	Compart -ment	Unit	Total
Chloride	Water	kg	2237.1
Chlorinated solvents, unspecified	Soil	kg	8.995269
	Compart -ment	Unit	Total
Chlorine			
Chloroform	Water	g	41.06047
Chloroform	Air	mg	36.3166
Chlorothalonil	Water	ng	166.9262
Chromate	Soil	mg	369.1125
Chromium	Water	g	29.34599
Chromium	Air	g	99.37018
Chromium	Water	g	389.5914
Chromium-51	Soil	g	3.946305
Chromium-51	Air	mBq	305.449
Chromium VI	Water	Bq	3814.919
Chromium VI	Air	g	2.236256
Chromium VI	Water	g	197.3833
Chromium, 25.5 in chromite, 11.6% in crude ore, in ground	Soil	g	20.70346
Chromium, ion	Raw	kg	26.63334
Chrysotile, in ground	Water	g	10.35828
Cinnabar, in ground	Raw	mg	884.3649
Clay, bentonite, in ground	Raw	mg	81.1826
Clay, unspecified, in ground	Raw	kg	400021.5
Coal, 26.4 MJ per kg, in ground	Raw	kg	406731.8
Coal, 29.3 MJ per kg, in ground	Raw	kg	41502.37
Coal, brown, in ground	Raw	kg	1.19748
Coal, hard, unspecified, in ground	Raw	kg	5205.939
Cobalt	Raw	kg	53545.65
Cobalt	Air	g	39.71033
Cobalt	Water	g	100.598
Cobalt-57	Soil	mg	9.817169
Cobalt-58	Water	Bq	115.2274
Cobalt-58	Air	mBq	425.3503
Cobalt-60	Water	Bq	16879.86
Cobalt-60	Air	Bq	3.757574

Substance	Compartment	Unit	Total
COD, Chemical Oxygen Demand	Raw	mg	193.2256
Copper	Water	kg	565.1667
Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	Raw	kg	1.285285
Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore, in ground	Raw	kg	7.124318
Copper, 1.42% in sulfide, Cu 0.81% and Mo 8.2E-3% in crude ore, in ground	Raw	kg	1.887254
Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore, in ground	Raw	kg	9.373912
Copper, ion	Water	g	357.4099
Cumene	Air	g	14.42066
Cumene	Water	g	34.65263
Cyanide	Air	g	2.411472
Cyanide	Water	g	110.9148
Cypermethrin	Soil	µg	72.05039
Diatomite, in ground	Raw	mg	5.576355
Dichromate	Water	mg	539.9518
Dinitrogen monoxide	Air	kg	5.681665
Dinoseb	Soil	mg	100.3233
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	Air	µg	893.4667
DOC, Dissolved Organic Carbon	Water	kg	81.32314
Dolomite, in ground	Raw	kg	2.216121
Energy, from hydro power	Raw	GJ	3.807802
Energy, gross calorific value, in biomass	Raw	MJ	23753.88
Energy, kinetic, flow, in wind	Raw	MJ	4001.433
Energy, potential	Raw	MJ	251230.4
Energy, solar	Raw	MJ	265.4485
Ethane	Air	kg	1.121864
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	Air	g	7.700267
Ethane, 1,2-dichloro-	Air	g	2.298151
Ethane, 1,2-dichloro-	Water	mg	156.2159
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	Air	mg	552.9014
Ethane, hexafluoro-, HFC-116	Air	mg	704.4158
Ethanol	Air	g	12.48995
Ethene	Air	g	182.5698
Ethene	Water	g	4.56665
Ethene, chloro-	Air	g	4.746743
Ethene, chloro-	Water	mg	104.2789
Ethene, tetrachloro-	Air	g	1.460897
Ethene, trichloro-	Air	g	1.400417
Ethylene diamine	Air	µg	96.80503
Ethylene diamine	Water	µg	234.6789
Ethylene oxide	Air	g	2.812336
Ethylene oxide	Water	mg	3.096061
Ethyne	Air	g	4.039766
Feldspar, in ground	Raw	mg	17.49542
Fenpiclonil	Soil	mg	14.99443
Fluoride	Water	g	620.7838
Fluoride	Soil	g	45.07005
Fluorine	Air	g	1.453593
Fluorine, 4.5% in apatite, 1% in crude ore, in ground	Raw	g	74.64517
Fluorine, 4.5% in apatite, 3% in crude ore, in ground	Raw	g	33.75917
Fluorspar, 92%, in ground	Raw	kg	2.995392
Fluosilicic acid	Air	mg	823.3776
Fluosilicic acid	Water	g	1.481915
Formaldehyde	Air	kg	47.79536
Formaldehyde	Water	g	2.579752
Gas, mine, off-gas, process, coal mining/m3	Raw	m3	849.8613

Substance	Compart-ment	Unit	Total
Granite, in ground	Raw	g	5.462794
Gravel, in ground	Raw	kg	20601.79
Gypsum, in ground	Raw	g	9.313789
Heat, waste	Air	MJ	4562373
Heat, waste	Water	MJ	24529.35
Heat, waste	Soil	MJ	2260.565
Helium	Air	g	289.2278
Heptane	Air	g	529.3686
Hexane	Air	kg	1.177833
Hydrocarbons, aliphatic, alkanes, cyclic	Air	mg	59.30327
Hydrocarbons, aliphatic, alkanes, unspecified	Air	g	508.0451
Hydrocarbons, aliphatic, alkanes, unspecified	Water	g	241.8449
Hydrocarbons, aliphatic, unsaturated	Air	g	79.79579
Hydrocarbons, aliphatic, unsaturated	Water	g	22.32415
Hydrocarbons, aromatic	Air	g	99.6981
Hydrocarbons, aromatic	Water	g	989.0485
Hydrocarbons, chlorinated	Air	g	2.043726
Hydrocarbons, unspecified	Air	kg	10.63644
Hydrocarbons, unspecified	Water	g	174.906
Hydrogen	Air	g	181.974
Hydrogen	Water	g	3.522
Hydrogen-3, Tritium	Air	Bq	8189224
Hydrogen-3, Tritium	Water	Bq	6.72E+08
Hydrogen chloride	Air	kg	15.04155
Hydrogen fluoride	Air	kg	1.273228
Hydrogen peroxide	Water	mg	196.0804
Hydrogen sulfide	Air	g	92.09931
Hydrogen sulfide	Water	g	28.41179
Hydroxide	Water	g	1.2979
Hypochlorite	Water	g	8.776549
Iodide	Water	g	186.6905

Substance	Compart-ment	Unit	Total
Iodine-129	Air	Bq	1559.276
Iodine-131	Air	Bq	44296.86
Iodine-131	Water	Bq	193.4986
Iodine-133	Air	Bq	23.51053
Iodine-133	Water	Bq	32.11383
Iron	Air	g	47.03497
Iron	Water	kg	6.037161
Iron	Soil	kg	3.470338
Iron-59	Water	Bq	8.828779
Iron ore, in ground	Raw	g	704.4
Iron, 46% in ore, 25% in crude ore, in ground	Raw	kg	951.4654
Iron, ion	Water	kg	22.20346
Isocyanic acid	Air	mg	592.1308
Kaolinite, 24% in crude ore, in ground	Raw	g	959.2145
Kerosene	Air	g	32.19596
Kieserite, 25% in crude ore, in ground	Raw	g	3.714461
Krypton-85	Air	Bq	392525.5
Krypton-85m	Air	Bq	288403.7
Krypton-87	Air	Bq	66981.83
Krypton-88	Air	Bq	86359.93
Krypton-89	Air	Bq	35680.32
Lanthanum-140	Air	Bq	1.680498
Lanthanum-140	Water	Bq	54.48406
Lead	Air	g	149.6274
Lead	Water	g	111.868
Lead	Soil	mg	421.7377
Lead-210	Air	Bq	3371.969
Lead-210	Water	Bq	2042.528
Lead, 5%, in sulfide, Pb 2.97% and Zn 5.34% in crude ore, in ground	Raw	kg	9.050167
Limestone, in ground	Raw	kg	2406.228
Linuron	Soil	mg	105.8849
m-Xylene	Air	mg	451.0673
Magnesite, 60% in crude ore, in ground	Raw	kg	383.28
Magnesium	Air	g	29.56683
Magnesium	Water	kg	19.12399
Magnesium	Soil	g	513.101

Substance	Compartment	Unit	Total
Mancozeb	Soil	mg	480.5465
Manganese	Air	g	38.86662
Manganese	Water	kg	3.400596
Manganese	Soil	g	34.40243
Manganese-54	Air	mBq	156.4237
Manganese-54	Water	Bq	1015.911
Manganese, 35.7% in sedimentary deposit, 14.2% in crude ore, in ground	Raw	kg	5.517857
Mercury	Air	g	39.96402
Mercury	Water	g	1.434173
Mercury	Soil	µg	448.8764
Metaldehyde	Soil	µg	624.3863
Metallic ions, unspecified	Water	kg	53.79745
Metals, unspecified	Air	g	748.0721
Methane	Air	kg	1225.683
Methane, biogenic	Air	g	509.9106
Methane, bromochlorodifluoro-, Halon 1211	Air	mg	120.9542
Methane, bromotrifluoro-, Halon 1301	Air	g	1.881801
Methane, chlorodifluoro-, HCFC-22	Air	mg	621.9715
Methane, dichloro-, HCC-30	Air	g	6.660529
Methane, dichloro-, HCC-30	Water	g	15.72274
Methane, dichlorodifluoro-, CFC-12	Air	µg	879.633
Methane, dichlorofluoro-, HCFC-21	Air	ng	166.9262
Methane, fossil	Air	kg	659.449
Methane, monochloro-, R-40	Air	ng	770.4647
Methane, tetrachloro-, CFC-10	Air	g	5.84828
Methanol	Air	g	87.92235
Metolachlor	Soil	mg	766.29
Metribuzin	Soil	mg	16.88989
Mineral waste	Waste	g	493.08
Molybdenum	Air	mg	781.6325
Molybdenum	Water	g	21.17762
Molybdenum	Soil	mg	2.515792
Molybdenum-99	Water	Bq	18.78494
Molybdenum, 0.010% in sulfide, Mo 8.2E-3% and Cu 1.83% in crude ore, in ground	Raw	g	174.202
Molybdenum, 0.014% in sulfide, Mo 8.2E-3% and Cu 0.81% in crude ore, in ground	Raw	g	24.78923
Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36% in crude ore, in ground	Raw	kg	1.93194
Molybdenum, 0.025% in sulfide, Mo 8.2E-3% and Cu 0.39% in crude ore, in ground	Raw	g	90.95923
Molybdenum, 0.11% in sulfide, Mo 4.1E-2% and Cu 0.36% in crude ore, in ground	Raw	kg	3.899089
Monoethanolamine	Air	g	2.106164
N-Nitrodimethylamine	Air	mg	314.9693
Naphthalene	Air	g	2.096777
Napropamide	Soil	mg	1.104975
Nickel	Air	g	555.4942
Nickel	Soil	mg	655.1705
Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore, in ground	Raw	g	336.2329
Nickel, ion	Water	g	493.4364
Niobium-95	Air	mBq	18.56886

Substance	Compart -ment	Unit	Total
Nitrate	Air	mg	648.4777
Nitrate	Water	kg	1.060137
Nitrite	Water	g	6.428421
Nitrogen	Water	g	247.4557
Nitrogen oxides	Air	kg	68434.73
Nitrogen, organic bound	Water	g	396.7063
NMVOC, non-methane volatile organic compounds, unspecified origin	Air	kg	26450.91
Noble gases, radioactive, unspecified	Air	Bq	1.50E+10
Oil, crude, 42 MJ per kg, in ground	Raw	kg	2282370
Oil, crude, 42.7 MJ per kg, in ground	Raw	kg	3624.138
Oil, crude, in ground	Raw	kg	37657.95
Oils, biogenic	Soil	g	77.72298
Oils, unspecified	Water	kg	308.9632
Oils, unspecified	Soil	kg	58.08962
Olivine, in ground	Raw	mg	622.8242
Orbencarb	Soil	mg	91.14542
Organic substances, unspecified	Air	kg	33966.23
Organic substances, unspecified	Water	kg	25.51745
Ozone	Air	g	492.6795
PAH, polycyclic aromatic hydrocarbons	Air	g	13.85514
PAH, polycyclic aromatic hydrocarbons	Water	g	11.47313
Paraffins	Air	µg	470.7666
Paraffins	Water	mg	1.366211
Particulates, < 10 um	Air	kg	8932.057
Particulates, < 2.5 um	Air	kg	54.67426
Particulates, > 10 um	Air	kg	196.0131
Particulates, > 2.5 um, and < 10um	Air	kg	69.23601
Particulates, SPM	Air	kg	1.0566
Pd, Pd 2.0E-4%, Pt 4.8E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	Raw	mg	40.36301
Pd, Pd 7.3E-4%, Pt 2.5E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	Raw	mg	97.00412
Peat, in ground	Raw	g	282.1022
Pentane	Air	kg	3.081799
Phenol	Air	g	58.99336
Phenol	Water	g	341.6386
Phenol, pentachloro-	Air	mg	223.6849
Phosphate	Water	kg	2.1121
Phosphorus	Air	g	1.9016
Phosphorus	Water	g	13.07878
Phosphorus	Soil	g	35.69669
Phosphorus, 18% in apatite, 12% in crude ore, in ground	Raw	g	155.3427
Phosphorus, 18% in apatite, 4% in crude ore, in ground	Raw	g	298.5807
Pirimicarb	Soil	µg	660.5302
Platinum	Air	µg	263.8523
Plutonium-238	Air	µBq	212.7105
Plutonium-alpha	Air	µBq	487.6117
Polonium-210	Air	Bq	5508.636
Polonium-210	Water	Bq	2494.878
Polychlorinated biphenyls	Air	mg	15.278
Potassium	Air	g	98.40232
Potassium	Soil	g	243.1947
Potassium-40	Air	Bq	463.4533
Potassium-40	Water	Bq	1588.558
Potassium, ion	Water	kg	10.79448
Propanal	Air	mg	22.29806
Propane	Air	kg	2.439221
Propene	Air	g	117.6305
Propene	Water	g	13.49245
Propionic acid	Air	g	1.107136
Propylene oxide	Air	mg	374.8433

Substance	Compartment	Unit	Total
Protactinium-234	Air	Bq	268.7632
Protactinium-234	Water	Bq	4977.096
Pt, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	Raw	mg	1.254956
Pt, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	Raw	mg	4.498833
Radioactive species, alpha emitters	Water	Bq	3.5017
Radioactive species, Nuclides, unspecified	Water	Bq	1518580
Radioactive species, other beta emitters	Air	Bq	8950.189
Radioactive species, unspecified	Air	kBq	2248181
Radium-224	Water	Bq	93017.28
Radium-226	Air	Bq	9508.447
Radium-226	Water	Bq	3246281
Radium-228	Air	Bq	553.67
Radium-228	Water	Bq	186034.6
Radon-220	Air	Bq	6.513266
Radon-222	Air	Bq	3.57E+10
Rh, Rh 2.0E-5%, Pt 2.5E-4%, Pd 7.3E-4%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	Raw	µg	920.1367
Rh, Rh 2.4E-5%, Pt 4.8E-4%, Pd 2.0E-4%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	Raw	mg	2.881986
Rhenium, in crude ore, in ground	Raw	mg	3.616401
Rubidium	Water	g	18.79582
Ruthenium-103	Air	mBq	4.079699
Ruthenium-103	Water	Bq	3.963791
Rutile, in ground	Raw	µg	998.2721
Scandium	Air	mg	9.738048
Selenium	Air	g	25.9192
Selenium	Water	g	4.693686
Shale, in ground	Raw	g	4.809217
Silicon	Air	g	124.12
Silicon	Water	kg	180.9699
Silicon	Soil	g	106.0092
Silicon tetrafluoride	Air	mg	2.257392
Silver	Air	µg	54.5893
Silver	Soil	mg	1.828342
Silver-110	Air	mBq	40.43294
Silver-110	Water	Bq	14603.27
Silver, 0.01% in crude ore, in ground	Raw	mg	125.7065
Silver, ion	Water	g	2.084357
Slags	Waste	g	176.1
Sodium	Air	g	46.78797
Sodium	Soil	kg	1.26098
Sodium-24	Water	Bq	142.1318
Sodium chlorate	Air	mg	48.53777
Sodium chloride, in ground	Raw	kg	81.33329
Sodium dichromate	Air	mg	146.1075
Sodium formate	Air	mg	5.055041
Sodium formate	Water	mg	12.14443
Sodium sulphate, various forms, in ground	Raw	g	593.4739
Sodium, ion	Water	kg	584.161
Solids, inorganic	Water	kg	19.53745
Solved solids	Water	kg	10438.33
Soot	Air	g	840
Stibnite, in ground	Raw	µg	579.5036
Strontium	Air	g	2.389902
Strontium	Water	kg	11.55865
Strontium	Soil	g	6.280742
Strontium-89	Water	Bq	318.6549
Strontium-90	Water	Bq	1219551
Styrene	Air	mg	2.844172
Sulfate	Air	g	239.1077
Sulfate	Water	kg	440.9816
Sulfide	Water	g	3.69414
Sulfite	Water	g	24.6712
Sulfur	Water	g	164.0935
Sulfur	Soil	g	379.4757

Substance	Compart-ment	Unit	Total
Sulfur hexafluoride	Air	g	5.20434
Sulfur oxides	Air	kg	18548.89
Sulfur, in ground	Raw	g	85.36548
Sulfuric acid	Water	kg	2.122867
Suspended solids, unspecified	Water	kg	255.7615
Sylvite, 25 % in sylvinite, in ground	Raw	g	893.0491
t-Butyl methyl ether	Air	g	20.54969
t-Butyl methyl ether	Water	g	2.072111
Talc, in ground	Raw	g	100.5843
Tebutam	Soil	mg	2.618638
Technetium-99m	Water	Bq	431.7227
Teflubenzuron	Soil	mg	1.124743
Tellurium-123m	Water	Bq	47.61204
Tellurium-132	Water	Bq	1.087685
Thallium	Air	g	11.75884
Thallium	Water	mg	238.8486
Thorium	Air	mg	13.90648
Thorium-228	Air	Bq	106.0934
Thorium-228	Water	Bq	372079.7
Thorium-230	Air	Bq	999.805
Thorium-230	Water	Bq	679076.2
Thorium-232	Air	Bq	133.222
Thorium-232	Water	Bq	276.7945
Thorium-234	Air	Bq	268.8193
Thorium-234	Water	Bq	4977.696
Tin	Air	g	9.781929
Tin	Soil	mg	3.28607
Tin, 79% in cassiterite, 0.1% in crude ore, in ground	Raw	g	216.9115
Tin, ion	Water	g	21.18417
TiO2, 45-60% in Ilmenite, in ground	Raw	kg	2.398197
Titanium	Air	g	2.83648
Titanium	Soil	mg	653.9969
Titanium, ion	Water	g	874.3483
TOC, Total Organic Carbon	Water	kg	81.64139
Toluene	Air	kg	1.608608
Toluene	Water	g	228.4336
Tributyltin compounds	Water	g	1.998047
Tungsten	Water	g	3.091619
Ulexite, in ground	Raw	g	1.958015
Uranium	Air	mg	17.25442
Uranium-234	Air	Bq	3139.737
Uranium-234	Water	Bq	5972.516
Uranium-235	Air	Bq	152.2992
Uranium-235	Water	Bq	9854.651
Uranium-238	Air	Bq	3456.323
Uranium-238	Water	Bq	16050.74
Uranium alpha	Air	Bq	14668.72
Uranium alpha	Water	Bq	286737.5
Uranium, 2291 GJ per kg, in ground	Raw	g	168.8611
Uranium, in ground	Raw	kg	1.09848
Vanadium	Air	g	80.83799
Vanadium	Soil	mg	18.71948
Vanadium, ion	Water	g	95.2165
Vermiculite, in ground	Raw	g	64.30087
VOC, volatile organic compounds	Air	kg	49.8
VOC, volatile organic compounds, unspecified origin	Water	g	663.0046
Volume occupied, final repository for low-active radioactive waste	Raw	l	2.264902
Volume occupied, final repository for radioactive waste	Raw	cm3	505.7265
Volume occupied, reservoir	Raw	m3y	3357.712
Volume occupied, underground deposit	Raw	cm3	975.286
Waste, solid	Waste	kg	40969.58
water	Air	kg	22.04728
Water, cooling, unspecified natural origin/m3	Raw	m3	666.5688
Water, lake	Raw	m3	67.4917
Water, river	Raw	m3	590.6235
Water, salt, ocean	Raw	m3	47.35094
Water, salt, sole	Raw	m3	20.56091

Substance	Compartment	Unit	Total
Water, unspecified natural origin/kg	Raw	kg	193.71
Water, unspecified natural origin/m3	Raw	m3	1632.154
Water, well, in ground	Raw	m3	254.4984
Wood and wood waste, 9.5 MJ per kg	Raw	kg	1633.398
Wood, hard, standing	Raw	l	563.0548
Wood, soft, standing	Raw	m3	1.789137
Wood, unspecified, standing/m3	Raw	cm3	41.3307
Xenon-131m	Air	Bq	347444.2
Xenon-133	Air	Bq	12603688
Xenon-137	Air	Bq	97675.15
Xenon-133m	Air	Bq	15035.54
Xenon-135	Air	Bq	5049175
Xylene	Air	kg	1.385372
Xylene	Water	g	183.0967
Zinc	Air	g	172.9168
Zinc	Soil	g	67.63812
Zinc-65	Air	mBq	781.0616
Zinc-65	Water	Bq	1926.986
Zinc 9%, in sulfide, Zn 5.34% and Pb 2.97% in crude ore, in ground	Raw	kg	10.07699
Zinc, ion	Water	g	971.9011
Zirconium	Air	mg	18.9269
Zirconium-95	Air	mBq	763.458
Zirconium-95	Water	Bq	22.31504

APPENDIX B

CONTRIBUTION ANALYSIS

Table B.1 Contribution of processes (Normalized values)

Processes by Impact-category	MNA	Bioventing	Chemical Oxidation	In – situ S/S	Ex – situ S/S
ADP					
Passenger car, operation	5.92E-10	2.46E-10	-	-	-
Coal at mine	-	3.99E-10	2.46E-10	4.45E-09	4.45E-09
Natural gas, at production	-	1.12E-10	-	-	-
Residual Fuel Oil (RFO)	-	1.30E-11	-	-	-
Hydrogen, cracking	-	-	1.26E-10	-	-
Natural gas, at production	-	-	3.10E-10	-	-
Petrol	-	-	1.30E-10	3.94E-10	-
Crude lignite at mine	-	-	3.08E-11	-	-
Crude oil, at production	-	-	1.01E-10	4.77E-09	-
Distillate Fuel Oil (DFO)	-	-	2.44E-11	1.61E-08	3.19E-07
GWP					
Passenger car, operation	3.63E-10	1.60E-10	8.51E-11	-	-
Coal into electricity boilers	-	2.22E-10	6.62E-11	-	-
Coal into industrial boilers	-	1.38E-11	-	-	-
Nat. gas into electr. boilers	-	1.97E-11	-	-	-
Nat. gas into industr. boilers	-	1.85E-11	9.74E-10	-	-
RFO into electricity boilers	-	6.84E-12	-	-	-
Tractor-trailer (diesel)	-	-	1.27E-11	5.86E-09	1.63E-07
Heavy fuel oil, burned in industrial furnace	-	-	2.50E-11	-	-
Hydrogen, cracking,	-	-	1.86E-11	-	-
Pig iron, at plant	-	-	2.16E-11	-	-
Sinter, iron, at plant	-	-	1.33E-11	-	-
Clinker, at plant	-	-	-	1.86E-08	1.86E-08
Diesel equipment	-	-	-	2.53E-09	3.80E-09
Distillate Fuel Oil (DFO)	-	-	-	9.94E-10	1.97E-08
ODP					
Chlorine gas, diaphragm cell	-	6.20E-14	-	-	-

Processes by Impact-category	MNA	Bioventing	Chemical Oxidation	In – situ S/S	Ex – situ S/S
Coal into electricity boilers	-	3.62E-13	-	-	-
RFO into electricity boilers	-	1.64E-13	-	-	-
Crude oil production	-	-	1.70E-12	4.39E-11	3.85E-11
Dichloromethane, at plant	-	-	1.03E-13	-	-
Tetrachloroethylene, at plant	-	-	2.31E-13	-	-
Transport, natural gas, long distance	-	-	9.08E-13	-	-
Chlorine gas, mercury cell	-	1.45E-13	1.44E-13	-	-
HTP					
Passenger car, operation	1.97E-12	8.20E-13	-	3.79E-11	3.79E-11
Coal into electricity boilers	-	9.43E-12	-	-	-
Coal into industrial boilers	-	1.73E-12	-	-	-
Copper, primary, at refinery	-	1.96E-13	-	3.35E-11	-
Diesel, burned in building machine	-	2.54E-13	-	-	9.82E-11
Ethyl benzene, at plant	-	3.27E-13	-	-	-
RFO into electricity boilers	-	8.00E-13	-	-	-
Anthraquinone, at plant	-	-	5.68E-10	-	-
Ferrochromium, high-carbon, 68% Cr, at plant	-	-	1.89E-10	1.09E-10	1.09E-10
Ferromanganese, 74.5% Mn, at regional storage	-	-	9.60E-12	-	-
Ferronickel, 25% Ni, at plant	-	-	1.18E-11	-	-
Heavy fuel oil, burned in industrial furnace	-	-	1.18E-11	-	-
Sinter, iron, at plant	-	-	1.17E-11	-	-
Discharge, produced water, onshore	-	-	-	5.49E-11	5.49E-11
Tractor-trailer (diesel)	-	-	-	5.15E-11	1.43E-09
Diesel equipment	-	-	-	4.76E-11	7.13E-11
Clinker, at plant	-	-	-	2.73E-10	2.73E-10
Distillate Fuel Oil (DFO)	-	-	-	3.64E-11	7.24E-10
FAETP					
Coal into electricity boilers	-	1.06E-12	-	-	-
Coal into industrial boilers	-	2.91E-13	-	-	-

Processes by Impact-category	MNA	Bioventing	Chemical Oxidation	In – situ S/S	Ex – situ S/S
Discharge, produced water, onshore	-	6.29E-13	-	2.75E-10	2.75E-10
Disposal, average incineration residue, to residual material landfill	-	3.59E-13	-	-	-
Disposal, coal ash, to residual material landfill	-	2.41E-12	-	1.07E-10	1.07E-10
Disposal, municipal solid waste, to municipal incineration	-	4.43E-13	7.36E-10	1.71E-10	1.71E-10
Disposal, nickel smelter slag, to residual material landfill	-	4.10E-12	1.72E-09	6.58E-10	6.58E-10
Disposal, red-mud from bauxite digestion, to residual material landfill	-	2.49E-13	1.35E-10	6.52E-11	6.52E-11
Disposal, slag, to residual material landfill	-	7.82E-13	5.41E-10	1.84E-10	-
Disposal, sludge from steel rolling, to residual material landfill	-	3.28E-13	1.68E-10	8.08E-11	8.08E-11
Disposal, steel, to municipal incineration	-	3.22E-13		-	-
Iron ore, 65% Fe, at beneficiation	-	4.22E-13	2.47E-10	-	8.36E-11
Natural gas	-	1.43E-12		8.36E-11	-
Coal tailings in landfill U	-	-	4.83E-11		-
Clinker, at plant	-	-	-	4.71E-11	4.71E-11
Magnesium oxide, at plant	-	-	-	3.94E-11	3.94E-11
Distillate Fuel Oil (DFO)	-	-	-	3.11E-11	6.19E-10
Heavy fuel oil, burned in industrial furnace	-	-	-	2.39E-11	-
Diesel equipment	-	-	-	1.29E-10	1.93E-10
MAETP					
Coal into electricity boilers	-	8.66E-09	1.75E-09	1.11E-08	4.95E-09
Coal tailings in landfill	-	-	4.63E-10	-	-
Disposal, lignite ash, to opencast refill	-	-	5.02E-10	1.42E-09	1.42E-09

Processes by Impact-category	MNA	Bioventing	Chemical Oxidation	In – situ S/S	Ex – situ S/S
Disposal, municipal solid waste, to municipal incineration	-	-	1.12E-09	-	-
Disposal, nickel smelter slag, to residual material landfill	-	-	5.61E-09	2.15E-09	2.15E-09
Disposal, red-mud from bauxite digestion, to residual material landfill	-	-	5.46E-10	-	-
Disposal, slag, to residual material landfill	-	-	1.93E-09	-	-
Disposal, sludge from steel rolling, to residual material landfill	-	-	4.58E-10	-	-
Hard coal, burned in industrial furnace	-	-	2.27E-09	-	-
Heavy fuel oil, burned in industrial furnace	-	-	1.05E-09	7.79E-10	-
Iron ore, 65% Fe, at beneficiation	-	-	4.97E-10	-	-
Pellets, iron, at plant	-	-	1.36E-09	-	-
Sinter, iron, at plant	-	-	4.06E-10	-	-
Discharge, produced water, onshore	-	-	-	2.25E-09	2.25E-09
Clinker, at plant	-	-	-	3.44E-09	3.44E-09
Aluminum, primary, liquid, at plant	-	-	-	1.08E-09	-
Ammonia, steam reforming, liquid, at plant	-	-	-	4.70E-10	-
Pellets, iron, at plant	-	-	-	4.62E-10	-
TETP					
Chlorine, gaseous, mercury cell, at plant	-	1.57E-12	-	-	-
Coal into electricity boilers	-	3.25E-11	-	-	-
Coal into industrial boilers	-	2.12E-12	-	-	-
Mercury, liquid, at plant	-	1.54E-12	-	-	-
Polyvinylchloride, at plant	-	7.12E-13	-	-	-
RFO into electricity boilers	-	6.44E-13	-	-	-

Processes by Impact-category	MNA	Bioventing	Chemical Oxidation	In – situ S/S	Ex – situ S/S
Transmission network, electricity, medium voltage	-	1.26E-12	-	4.44E-10	4.44E-10
Anthraquinone, at plant	-	-	1.09E-10	-	-
Ferrochromium, 68% Cr, at plant	-	-	3.32E-11	-	-
Ferronickel, 25% Ni, at plant	-	-	1.24E-11	-	-
Heavy fuel oil, burned in industrial furnace	-	-	1.04E-10	6.73E-11	6.73E-11
Sinter, iron, at plant	-	-	1.86E-11	-	-
Steel, electric, un- and low-alloyed, at plant	-	-	3.07E-10	-	-
Clinker, at plant	-	-	-	3.27E-09	3.27E-09
Diesel equipment	-	-	-	1.11E-10	1.67E-10
Distillate Fuel Oil (DFO)	-	-	-	6.83E-11	1.36E-09
Natural gas, burned in production flare	-	-	-	4.59E-11	-
POCP					
Passenger car, operation	3.22E-12	4.93E-11	2.63E-11	1.89E-10	-
Coal into electricity boilers	-	3.15E-11	2.44E-12	-	-
Coal into industrial boilers	-	2.00E-12	-	-	-
Natural gas	-	1.42E-11	-	-	-
Uranium in electricity boilers	-	1.61E-12	-	-	-
Tractor-trailer (diesel)	-	-	1.75E-12	-	-
Hard coal, burned in industrial furnace	-	-	4.20E-12	-	-
Heavy fuel oil, burned in industrial furnace	-	-	3.75E-12	2.36E-11	-
Hydrogen, cracking	-	-	1.00E-12	-	-
Sinter, iron, at plant	-	-	1.77E-11	-	-
Tractor-trailer (diesel)	-	-	-	8.07E-10	2.24E-08
Diesel equipment	-	-	-	3.72E-10	5.58E-10
Clinker, at plant	-	-	-	2.80E-10	-
Distillate Fuel Oil (DFO)	-	-	-	2.25E-10	4.46E-09
AP					
Coal into electricity boilers	-	2.71E-10	6.90E-11	-	-
Coal into industrial boilers	-	1.65E-11	-	-	-

Processes by Impact-category	MNA	Bioventing	Chemical Oxidation	In – situ S/S	Ex – situ S/S
Natural gas	-	1.00E-10	-	-	-
Passenger car, operation	1.60E-10	7.56E-11	3.41E-11	-	-
RFO into electricity boilers	-	7.61E-12	-	-	-
Heavy fuel oil, burned in industrial furnace	-	-	3.18E-11	-	-
Hydrogen, cracking	-	-	1.00E-11	-	-
Operation, lorry 32t	-	-	3.57E-12	-	-
Petrol I	-	-	8.34E-12	-	-
Sinter, iron, at plant	-	-	1.25E-11	-	-
Anthraquinone, at plant	-	-	5.36E-12	-	-
Blasting	-	-	9.82E-12	-	-
Tractor-trailer (diesel)	-	-	-	4.85E-09	1.35E-07
Diesel equipment	-	-	-	3.84E-09	5.75E-09
Clinker, at plant	-	-	-	2.82E-09	2.82E-09
Distillate Fuel Oil (DFO)	-	-	-	1.65E-09	3.28E-08
Diesel, burned in building machine	-	-	-	2.04E-10	-
EP					
Coal into electricity boilers	-	3.39E-11	-	-	-
Coal into industrial boilers	-	2.30E-12	-	-	-
Nat. gas into electr. boilers	-	2.67E-12	-	-	-
Nat. gas into industr. boilers	-	2.01E-12	1.27E-12	-	-
Passenger car, operation	1.50E-10	4.10E-11	2.04E-11	6.13E-11	-
Uranium in electricity boilers	-	1.05E-12	-	-	-
Blasting	-	-	5.85E-12	-	-
Hydrogen peroxide, 50% in H2O, at plant	-	-	4.04E-12	-	-
Crude oil, at production onshore	-	-	1.57E-12	-	-
Diesel, burned in building machine	-	-	1.43E-12	1.22E-10	-
Disposal, basic oxygen furnace wastes, to residual material landfill	-	-	1.36E-11	-	-
Heavy fuel oil, burned in industrial furnace 1MW, non-modulating/RER U	-	-	2.30E-12	-	-
Hydrogen, cracking	-	-	2.85E-12	-	-

Processes by Impact-category	MNA	Bioventing	Chemical Oxidation	In – situ S/S	Ex – situ S/S
Iron ore, 65% Fe, at beneficiation	-	-	4.88E-12	-	-
Operation, lorry 32t	-	-	2.15E-12	-	-
Tractor-trailer (diesel)	-	-	-	2.17E-09	6.03E-08
Diesel equipment	-	-	-	2.09E-09	3.14E-09
Clinker, at plant	-	-	-	1.01E-09	-
Distillate Fuel Oil (DFO)	-	-	-	1.30E-10	2.58E-09

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