29

THE USE OF LIFE CYCLE ASSESSMENT IN THE EVALUATION OF ENVIRONMENTAL PERFORMANCE IN THE BASE METAL REFINING INDUSTRY

By

Patricia Belinda Crosby Forbes

Dissertation submitted to the University of Cape Town
in fulfilment of the requirements for the degree of
Master of Applied Science

Department of Chemical Engineering
University of Cape Town
Rondebosch
7700

April 1999

TABLE OF CONTENTS

SYNOPSIS

In the last decade, life cycle assessment has come into consideration as an environmental decision support tool for the design and operation of industrial processes. The usefulness of this technique for the purpose of environmental management was assessed by means of a case study carried out at the base metal refinery of Impala Platinum Limited. An assessment was first carried out on the historic performance of the process. This was then extended to evaluate some possible impacts of future changes in operating practice and technology.

The assessment focussed on the activity of base metal refining, in which nickel, copper, and to a lesser extent cobalt, are produced from a sulphidic matte. The assessment included industrial processes which contribute utilities, and reagents (down to a consumption cut-off of 0.03t/t of nickel produced) to the refining process, although it should be noted that generalised database inventories were consulted for such processes. The production of the sulphidic matte was excluded from the study, in order to focus on the refining operation. The study was to the gate only, excluding all environmental concerns that could be associated with the products.

Monthly refinery operating data for the period 01/95 to 07/97 inclusive was collected from various process records, to obtain representative averages for inclusion in the overall base case life cycle inventory (LCI) and elemental mass balances in addition to monthly mass balances. These mass balances were verified by Senior Chemical Engineers of the BMR, and an overall accuracy of between 10 and 15% was estimated for the mass flows, based on the accuracy of the sources of data used.

The PEMS (Pira Environmental Management System, version 4) software package was used to translate the life cycle inventories into environmental profile scores. A functional unit of a ton of nickel produced was employed, as this is the primary product of the BMR, in terms of quantity and revenue generated. The following impact categories based on environmental problems were included in the profiles: global warming, resource depletion, acidification, eutrophication, smog, ecotoxicity (aquatic and terrestrial), human toxicity, ozone depletion, and water usage. Upon normalisation of the first five of these categories (for which provisional global normalisation factors have been derived), it was evident that resource depletion and

smog generation were the two impact categories upon which the BMR operations could have the largest relative potential impacts.

The dominant contributors to the impact scores were the steam generation process and electricity consumption. As both the electricity and steam are produced from coal combustion they both contributed primarily to the global warming, resource depletion, acidification, smog, water usage and aquatic ecotoxicity scores. The BMR effluent contributed significantly to the total aquatic ecotoxicity and eutrophication impact scores, as a worst case scenario in which the effluent percolates to groundwater was used. Ammonia consumption also contributed significantly to the total environmental profile scores (particularly to the resource depletion, terrestrial ecotoxicity, ozone depletion, and smog (ethene) impact categories), due to the potential impacts associated with its manufacture.

The results of sensitivity studies indicated that the exclusion of transport and reagents used in relatively small quantities from the LCI was valid, as there was no significant change in the environmental profile scores upon their inclusion.

In terms of the use of LCA in the determination of trends in environmental performance, it was found from the monthly environmental profiles that the unit environmental impact scores decreased with increasing nickel production. This was due to less efficient energy usage (primarily steam consumptions) at lower nickel throughputs, as a result of a large fixed energy load associated with the process. The exceptions to these trends of decreased unit impact scores with increased nickel production were the eutrophication and aquatic ecotoxicity scores, which were a function of the quantity of ammonia or nickel in the effluent, respectively. The effluent quality was not related to production volumes.

The application of this environmental model to the evaluation of environmental performance of different process options was then investigated, by means of three scenarios. Upon comparison of the environmental impacts associated with nickel sulphate processing with those of processing matte, it was found that each of the unit environmental impact scores were lower for the production of nickel from nickel sulphate. This was a result of reduced electricity and reagent requirements, due to the exclusion of milling, leaching and copper electrowinning.

DEDICATION

This thesis is dedicated to the memory of my
late mentor and lecturer,
Mrs Grace Ross,
whose exacting standards made giving
of my best a way of life.

ACKNOWLEDGEMENTS

The completion of this project would not have been possible without the support of the management of Impala Platinum Refineries and Head Office. I would therefore like to thank Dirk Theuninck, Stuart Murray, Geoff Skelton, Dr Lucas Van der Berg, Cliff Reynolds and Scott Stevenson in this regard, as well as for financial assistance.

I would also like to thank all of the employees of Impala Platinum Refineries Base Metal Refinery, who willingly gave of their time to help me assemble data for the project. A few deserve mention by name: Barry Gous, Apie Pelser, Jakkie Rudolph, Elise Schroeder, Steven Ralph, Martyn Fox, Timothy Spandiel, and Dirk du Toit. The support of the Impala Refineries SHEQ (Safety, Health, Environment and Quality) team, especially that of Stephen Engelbrecht, was greatly appreciated, as was the assistance of Elrina and Wendy of the library. I am also grateful for the time that Ian Smith put into proof-reading for me, to allow me to get "a glimpse of perfection"!

I extend my thanks to my supervisors at UCT, A-Prof. Peter Gaylard and A-Prof. James Petrie (who currently holds the Shell Chair of Environmental Engineering at the University of Sydney), as well as to Dr Harro von Blottnitz for his guidance. Thanks to the "Greenhouse" Chemical Engineering group for the interesting conversations, and to Craig Balfour for the invaluable IT support he provided. The financial assistance provided by the Foundation for Research and Development via THRIP (Technology and Human Resources for Industry Programme) is gratefully acknowledged.

On a more personal note, I would like to thank my friends and family for the interest they showed in my work and for their encouragement. Special thanks to my mom, for helping with the checking of the thesis. Finally, to my husband, Andrew, thank you for your support, for your scientific viewpoint on my project, and especially for giving me a push when I needed one!

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ACGIH	American Conference of Governmental Industrial Hygienists
ADI	Acceptable Daily Intake
AQG	Air Quality Guidelines
ATSDR	Agency for Toxic Substances and Disease Registry
BEO	Best Environmental Option
BHT	2,6-bis(1,1-dimethylethyl)-4-methyl phenol
BML	Base Metal Laboratory
BMR	Base Metal Refinery
CDI	Cobalt Development Institute
CFC	Chloro-fluoro-carbon
CSIR	Council for Scientific and Industrial Research
DEHPA	Di-2-ethylhexyl phosphoric acid
Demin	Demineralised / demineralisation
EB	Environmental Burden
EC_{50}	Effect concentrations for 50% of the organisms
EDTA	Ethylenediaminetetraacetic acid
EIA	Environmental Impact Assessment
EPA	Environmental Protection Agency
EPS	Environmental Priority Strategy
EQS	Environment Quality Standards
ERPM	East Rand Proprietary Mines
ETH	Eidgenössische Technische Hochschule
EUSES	European System for the Evaluation of Substances
FEMS	Far East Mixed Sulphides
GWP	Global Warming Potential
HSA	High Security Area
HTS	High Temperature Shift
ICME	International Council on Metals and the Environment
INCO	International Nickel Company
ISO	International Organisation for Standardisation
IT	Information Technology
IX	Ion Exchange
LC_{50}	Lethal concentrations for 50% of the organisms
LCA	Life Cycle Assessment
LCANET	The European consortium for advancing LCA practice
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
LD_{50}	Lethal dose for 50% of the organisms
LTS	Low Temperature Shift
MEA	Monoethanolamine
MEIM	Methodology for Environmental Impact Minimisation
MinPro	Impala Platinum Limited, Mineral Processes
MSDS	Material Safety Data Sheet
MTC	Maximum Tolerable Concentration
NEC	No Effect Concentration
NEPA	National Environmental Policy Act
NiDI	Nickel Development Institute
NiPERA	Nickel Producers' Environmental Research Association
NOEC	No Observed Effect Concentration
NOSA	National Occupational Safety Association
NTP	National Toxicology Programme

OEL	Occupational Exposure Limit
PEMS	Pira's Environmental Management System
PGMs	Platinum Group Metals
PMR	Precious Metal Refinery
RA	Risk Assessment
REPA	Resource and Environmental Profile Analysis
RIVM	National Institute for Public Health and Environmental Protection (Dutch)
RO	Reverse Osmosis
RSD	Relative Standard Deviation
RWB	Rand Water Board
SABS	South African Bureau of Standards
SETAC	Society of Environmental Toxicology and Chemistry
SHE	Safety, Health and Environment
SHEQ	Safety, Health, Environment and Quality
SX	Solvent Extraction
TAC	Tolerable Air Concentration
TCLP	Toxicity Characteristic Leaching Potential
TDI	Tolerable Daily Intake
TDS	Total Dissolved Solids
THRIP	Technology and Human Resources for Industry Programme
TNOA	Tri-n-octylamine
UN	United Nations
UNEP IE/PAC	United Nations Environment Programme: Industry and Environment Programme Activity Centre
USA	United States of America
USES	Uniform System for the Evaluation of Substances
VOC	Volatile Organic Compound
VSC	Virtually Safe Concentration
WHO	World Health Organisation
WMC	Western Mining Corporation

Chapter 1: INTRODUCTION

1.1) PROJECT INTRODUCTION

i) Environmental issues and life cycle assessment

Environmental studies are being initiated by industry for a number of reasons, including increasing pressure from environmentalists, increasing processing and waste disposal costs, expiring dumping concessions, and as a response to management commitment to good environmental practice. In the base metal refining industry, environmental pressure by environmentalists as well as the public has been intensified by concerns regarding the toxicity (particularly carcinogenicity) of metal species, including nickel and cobalt. Industry has responded to these concerns by initiating independent scientific toxicity studies (for example, those financed by the Nickel Producers' Environmental Research Association (NiPERA, 1999)).

Legislation in South Africa is rapidly embracing this trend and is currently progressing towards a more stringent and holistic approach to environmental regulation. Consequently, it is advantageous for companies to anticipate these changes in the legal climate and to initiate pro-active environmental studies and management systems, in order to prevent legal and corrective costs which could be incurred with future non-compliances.

The pro-active approach to responsible environmental management is encompassed by what has become known as the Precautionary Principle. The Bergen Conference Ministers Declaration (UN 1990, cited in Jackson, 1993) stated that

> *"environmental measures must anticipate, prevent and attack the causes of environmental degradation. Where there are threats of serious or irreversible environmental damage, lack of scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation".*

The importance of considering all possible environmental impacts of a company's operations is becoming increasingly evident, with the transfer of impacts to other, geographically removed, operations being considered unacceptable.

> "*Anthropogenic inputs into the environment of unnatural substances in unnaturally large quantities should be avoided, to the extent that preventing a release into one compartment of the environment does not cause environmental damage elsewhere. Where necessary, substances should be prioritised for action in relation to their liability to cause harm*" (Dethlefson, *et al*, 1993).

In determining this liability, one must consider all scientific knowledge available with respect to that substance, as well as its toxicity, degree of bioaccumulation, persistence in the environment, adverse health effects (such as carcinogenicity) and the natural fluxes of that substance in the ecosystem.

Life Cycle Assessment (LCA) serves as a useful tool in the identification and evaluation of environmental impacts associated with a product or process. The methodology encompasses a '*cradle to the grave*' philosophy that examines all aspects from the initial extraction of resources from the environment to the final disposal of the used product. In this way, a comprehensive assessment of the environmental performance of a product or process can be arrived at. In addition, LCA provides a structured audit trail, which tracks flows of resources through the production process, to their ultimate environmental impacts (due to consumption, transformation, or disposal). As such, LCA may provide valuable guidance on how to improve base-line environmental performance (Stewart and Petrie, 1997).

It is necessary for a change in focus to occur in all sectors of industry from '*Clean-up Technology*', which centres on pollution control and waste management, to '*Clean Technology*', which involves fundamental process changes to avoid the production of the pollutant or waste (Clift, 1993a). The latter option may also have economic advantages, as Clean-up technology always requires additions to processes. As environmental impacts have their origin in processes and the materials used, the processes or materials should be changed so as to minimise these impacts. LCA can be a useful tool in the application of Clean Technology strategies, as the Life Cycle approach is based on the premise that "waste is really evidence of inefficient use of materials" (Clift, 1993a). LCA also provides a useful means of comparing the environmental performance of alternative process options.

Hirschhorn, *et al*, (1993) sets out a hierarchy of preventive options, in which the greatest environmental improvements can be made by reducing material consumption and **changing to less polluting activities**. This requires the most drastic of changes, however, which are consequently the most difficult to make. Environmental impacts may be significantly minimised by changing the **composition of products** and improving their durability, or by the **reduction of material inputs** (or changing to less toxic alternatives). Finally, improved **process efficiencies** (achieved by better control and improved material handling) may also provide some decrease in impacts.

At the centre of environmental concerns is the issue of sustainable development, which the World Commission on the Environment and Development has defined as:

> "*...development that meets the needs of the present without compromising the ability of future generations to meet their own needs*"
> (World Commission on the Environment and Development, 1987).

Again emphasis has to shift from waste management to include the efficient use of resources and energy. In order for a company to move towards the practice of prevention, it is necessary that recognition be made that a good quality environment is an integral factor of sustainable industrial activities, and that good environmental management is important for the continuity of the company (Hirschhorn, *et al*, 1993).

It has been noted by Jacobs (1991) that the desire to protect the interests of future generations (the concept of sustainability), does not remove the desire to improve the well-being of the current one. Many policies, such as reducing emissions, which are put in place to secure sustainability, are also likely to improve current welfare, while others (such as recycling) may increase the gross national profit. However, most of the means by which living standards are currently raised cause environmental degradation through irresponsible resource consumption and pollution. Thus a conflict exists between sustainability and current economic growth patterns.

In order to reduce environmental impacts, both resource usage and pollution must be considered. For renewable resources, the sustainable output rates could be increased to some extent by increasing harvest rates without introducing other

forms of environmental degradation (for example, nutrification of water due to fertiliser run-off). For non-renewable resources, recycling is important. Pollution may also be reduced by increased recycling, although avoiding the production of waste is clearly preferable to recycling it (this could be achieved, for example, by the production of bio-degradable, durable products) (Jacobs, 1991). LCA evaluates the material and energy efficiencies of systems, and thereby indicates possible areas of improvement.

ii) The aim of the project

The role of LCA in quantifying the interdependence of resource extraction and resource consumption industries has been discussed with respect to the mineral processing industries in South Africa (Stewart and Petrie, 1996a, 1996b). In this study, it was noted that a small quantity of valuable products, which often supply value-adding operations in other parts of the world, are generated from a large quantity of raw materials. This leads to potentially large amounts of waste being generated. The study referred to was based on industry-wide averages and a number of theoretical values, and dealt primarily with waste inventories (Stewart and Petrie, 1996a). It was therefore decided to initiate a project focusing on base metal refining, and to use real process data by means of a case study of a particular refinery.

The aim of this project was to establish how LCA methodology could be of use in the evaluation of process options and establishment of trends with respect to environmental performance in the base metal refining industry. The complex metallurgy of base metals is evident from the wide range of extraction and refining technologies adopted, as will be discussed in section 2.2. Each base metal refinery has unique process features, and consequently has site specific environmental impacts and problems. Although the processes may be disparate between different refineries, LCA methodology as used in this case study could similarly be applied to other operations.

The environmental performance of the base metal refinery (BMR) at Impala Platinum Limited was examined as a case study for the application of life cycle assessment methodology to the base metal refining industry. In order to focus on the environmental performance of the BMR itself and thereby highlight potential

environmental improvement opportunities, a modified cradle-to-gate LCA was performed, whereby certain background processes (such as mining of the ore) were omitted. A workable framework or model was developed, which could be used to assess possible environmental impacts of changes in the process, be they expansions or changes in processing technologies. This was tested via three scenarios.

Impala Platinum Limited is the second largest producer of platinum in the world today, with an annual platinum production in excess of thirty tons. Other products include approximately fifteen tons of palladium and 10 000 tons of nickel per year. Impala Platinum Refineries is situated in Springs, Gauteng, South Africa. There are approximately 1000 employees at the Refineries complex, of which approximately 560 are employed in the Base Metal Refinery. The Refineries are situated in an environmentally sensitive location, being adjacent to a residential area and the Blesbokspruit watercourse, which was declared a Ramsar site (a Wetland of International Importance) on the second of October 1986. Thus stringent environmental monitoring programmes are followed, which are currently being assimilated according to ISO 14 001 environmental management standard specifications.

It has been noted that the "strategic environmental principles and goals of an organisation should guide the use of LCA and other techniques, so that these are consistent with an organisation's philosophy" (Vigon, 1997a). The Environmental Policy of Impala Platinum Limited Refineries states that (Impala, 1998):

> "*The Refineries recognises that its products, whilst leading to an improved quality of life, do have an impact on the environment during manufacture, use and disposal, and is committed to minimising their impact throughout their life cycle by pursuing best environmental practice wherever practical*".

It is therefore evident that Impala's philosophy is consistent with LCA principles.

iii) Thesis structure

The project involved the collection of relevant process data (Chapter 4), and the compilation of mass balances for the Life Cycle Inventory (LCI), after goals of the project and suitable system boundaries had been identified (Chapter 3). This information was then translated into environmental impacts (Chapter 5), and the

results assessed, both in terms of the greatest contributing factors and scope for improvements (Chapter 6).

Three scenarios were then investigated in order to test the robustness of this BMR LCA model for the environmental assessment of various process options. The scenarios covered a change in feedstock (Chapter 7), in plant technology (Chapter 8), and in waste management (Chapter 9). Following this, conclusions were drawn (Chapter 10), with emphasis on the applicability of LCA methodology for environmental performance optimisation in the base metal refining industry.

1.2) OVERVIEW OF THE HISTORY AND METHODOLOGY OF LCA

Christiansen (1993) provides an overview of the history of LCA, which refers back to the first studies which can be considered as partial life cycle assessments, which were performed in the late sixties and early seventies, when environmental issues were coming to the fore. Cost minimisation studies and use of alternative energy sources were the basis for environmental assessment techniques (such as "net energy analysis" studies, which were initially based solely on energy consumptions, but later included emissions and wastes (Azapagic, 1997)). This methodology was used in a number of countries, including Sweden, the UK, Switzerland and the USA (Udo de Haes, 1993a). Many other studies dealt with packaging materials. In 1969, the Coca Cola Company, for example, performed a study to compare different beverage containers, using a process which later became known as Resource and Environmental Profile Analysis (REPA) (Christiansen, 1993).

Life Cycle Inventory Analysis itself emerged as a tool for analysing environmental problems in the late eighties. By 1992, some ninety LCAs had been done, approximately half which dealt with the packaging industry. 10% were on products from the chemical and plastic industry and a similar quantity dealt with building materials and energy production (Christiansen, 1993). Due to a lack of a theoretical framework for these studies, the results of seemingly similar studies often yielded conflicting results. A Code of Practice regarding LCA applications was developed in the 1990s by the Society of Environmental Toxicology and Chemistry (SETAC), which has led to its more widespread use, and acceptance as a useful environmental tool.

LCA is defined by SETAC (1993) as:

> "*a process to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and material uses and releases to the environment; and to identify and evaluate opportunities to effect environmental improvements. The assessment included the entire life cycle of the product, process or activity, encompassing extracting and processing raw materials; manufacturing, transportation and distribution; use, re-use, maintenance; recycling, and final disposal*".

Procter and Gamble in the USA, and Volvo in Sweden are examples of international companies which have integrated LCA principles into their environmental strategies (Udo de Haes, 1993a). The International Organisation for Standardisation (ISO), is currently developing a series of standards (as part of the ISO 14 000 environmental management series) dealing with LCAs (ISO 14041 is the code for Goal and Scope Definition and Inventory Analysis, while ISO 14042 relates to Life Cycle Impact Assessment (LCIA)). This will standardise the methodology used, and will also have a positive impact on the number of LCAs performed by industry.

Four steps are followed when performing a life cycle assessment. Each of these steps will now be briefly discussed, whilst further details on each step may be found in the introductory sections of the relevant chapters. The SETAC LCA methodology was followed in this work.

The first stage involves **defining the goal and the scope of the project** (Chapter 3), where the purpose of the LCA, with respect to its application and the intended use of results, is clarified. Details regarding the system boundaries (what is to be included and reasons for exclusions) also need to be established at this stage. The subject of the study should be clearly defined, as well as the functional unit, which "describes the main function performed by a product and indicates how much of this function is considered" (Heijungs, 1992a). In the case of base metal refining, a functional unit could be "a ton of nickel produced per month". All inputs and outputs are related back to this functional unit, for example, reagent usage per ton of nickel produced, as are the environmental impacts incurred.

The second step involves data collection for the **inventory** of inputs and outputs (Chapter 4). Firstly, a suitable flowsheet for the processes which are to be studied is established. Attention then needs to be paid to the collection of data with respect to it being representative and of good quality, and a balance needs to be established between quantitative and qualitative information. Data is required in the following five categories: primary fuels and other service inputs (such as water and compressed air), raw materials, deposits to land, emissions to air and emissions to water (Crittenden,1994). An inventory mass balance table is then compiled, based on the masses of inputs and outputs. In this manner, the inventory provides an analysis of the environmental interventions during the product life cycle, in terms of measurable physical parameters.

It must be noted, however, that LCI data is presently lacking for wide sectors of industry, which can introduce bias because the process option which is less well documented may appear to be the most environmentally favourable, depending on the degree of information aggregation and how the results are interpreted (Vigon, 1998a). Another problem is that time and effort may be wasted by the duplication of work on background processes (those other than the process under investigation itself), such as reagent production processes. Allocation of inputs and outputs between multiple outputs of economic value (products) may also be necessary. Inventory analysis can then be used to identify opportunities for reducing emissions, energy and materials use (Fava, *et al*, 1993).

The third step in LCA is that of **impact assessment**. A sub-step of this is **classification** (Chapter 5). (As an aside, it is noted that this step of the process is currently being divided into a classification step and a characterisation step, although as this has not been finalised as yet (Guinée, 1998), the steps as laid out in Heijungs, 1992b will thus be used in this dissertation). According to the problem oriented approach, classification entails the selection of the environmental problem types to be investigated (such as the greenhouse effect or acidification), and the allocation of each item on the inventory list to one or more of these categories (Guinée, *et al*, 1993a). Another approach is the critical volumes method, which is based on units of polluted air and water (Heijungs, 1992b).

The classification stage of a LCA serves as a means of reducing the complexity of the inventory data, as well as rationalising the potential contributions of a product to the various environmental issues (Vigon, 1997b). It should be noted that the inventory phase of a LCA is based on a quantitative system, whilst this impact assessment phase introduces scientific uncertainties.

Classification factors are used to relate the contributions of each substance which is emitted by a process to each environmental problem. A reference substance is generally used to develop comparative factors, for example, the propensity of a substance to release protons as compared to sulphur dioxide for the environmental problem of acidification (sulphur dioxide thus has a classification factor of one). Current scientific evidence is used to link wastes with pollution impacts, although it is recognised that these may change as scientific progress occurs.

The potential environmental effects are then quantified to form an environmental profile by multiplying the amount of each substance by its relevant classification factor, and then adding up all the scores per environmental problem. As spatial and temporal information is not normally available, the potential impacts generally refer to the global scale. In order to determine the relative contributions to the total impacts in a region, a normalisation step is often included (normalisation is another sub-step of the impact assessment step). The contribution made by the product or process of interest to an environmental effect is linked to the contribution made by a given community to that problem over a given period of time (for example, the contribution to annual global emissions).

The environmental profile is then **evaluated** in the **Valuation** step, as is the validity and reliability of the results. The relative magnitude of the effect scores are compared for the different products or process options considered. The different environmental effects may be weighted and an overall score obtained. There is a degree of subjectivity associated with such a valuation step, thus it is not always included in a LCA. Broadly, there are three types of weighting strategies used in valuation: those based on monetary issues (willingness to pay), those related to sustainability and target environmental systems, and those based on social and expert opinions (Vigon, 1998b).

Sensitivity analyses are used to determine the effect of changes in input data on the environmental profile. The data relating to highly dependent results should be closely scrutinised to verify their accuracy (Denison, 1993). The sensitivity study includes a reliability analysis to determine the effects of uncertainties in the data (an acceptable margin of error is thus estimated), and a validity analysis to determine the effect of the assumptions and choices made on the conclusions reached.

Improvement assessment is the starting point for the redesign of products and processes. Substances and processes which dominate or contribute substantially to the various potential environmental effects are identified. These aspects may then form the focus of future improvements.

A complicating factor originates from the number of impacts which need to be considered simultaneously, as improvements in some of these impacts could well result in a deterioration in others (Azapagic, 1997). Stefanis *et al* (1995) used an example based on the production of dichloroethane to illustrate that a reduction in waste may, in fact, lead to an increase in overall emissions. An optimum must thus be established which takes into account all possible emissions which could arise (including those arising during waste stream purification, if appropriate). Methodology for Environmental Impact Minimisation (MEIM), which incorporates Life Cycle Assessment principles, was subsequently developed by these authors.

The impact and improvement assessment stages of LCA thus ensure that reduction strategies are optimised and that improvement programmes do not produce unanticipated impacts (Fava, *et al*, 1993). It should be noted that LCA may not be a complete assessment of environmental issues because cut-offs and gaps may exist with respect to boundaries as well as inputs and outputs. Further, impact category indicators have inherent limitations (section 5.3.4), and not all possible impact categories are included. The environmental profiles are models of LCI results, and are not an analysis of, or prediction for, actual environmental impacts (Vigon, 1997c). LCA is also a dynamic and iterative process of evaluation, therefore changes to inputs or updated impact data require changes to the inventory or impact assessment (Fava, *et al*, 1993).

It should be noted that the environmental profile relating to any multi-product system will be a function of the allocation methodology used in the LCA (Heijungs and

Frischknecht, 1998). It is generally accepted that allocation should be avoided wherever possible by dividing a unit process into sub-processes or by expanding the product system to include the additional functions related to co-products, as detailed in the ISO 14041 standard (ISO, 1998). Where allocation cannot be avoided, partitioning of inputs and outputs should be conducted based on physical or other relationships (such as economic value) between the products (ISO, 1998).

The US Environmental Protection Agency (EPA) has funded studies to assess the validity of various streamlining methods (Hunt, *et al*, 1998), which are used to reduce the scope, cost, or effort required to conduct a LCA. These are important to consider especially with respect to the industrial application of LCA. Streamlining methods may involve the removal of upstream and/or downstream components in a product's life cycle, such as reagent production or product use. Alternatively, exclusion of raw materials or reagents (based on their relative mass percentages of total inputs), or the use of qualitative or less accurate data may be decided on.

The success of a streamlining technique in providing results which compare favourably with those obtained from a full LCA, depends on the system studied (Hunt, *et al*, 1998). For example, the removal of upstream components may be suitable for product systems for which the LCI totals are dominated by the product manufacture. Generally speaking, the error increases with increasing omissions. It was noted that "estimates for raw materials steps may be adequate, but the final product steps must use high quality data", and for processes which contribute very little to the LCI total (for example, less than 1%), estimates or exclusions may be acceptable (Hunt, *et al*, 1998). However, inconsistent success rates were found regarding the use of surrogate processes (for example, data on propylene glycol used for ethylene glycol production). It was concluded that streamlined LCA methods may provide acceptable results, depending on the level of risk which is regarded as being acceptable. The validity of these methods thus ultimately depends on the product system being studied, the quality of the data, and the purpose of performing the LCA.

Due to the present use of a number of environmental management tools, including Environmental Impact Assessment (EIA), Risk Assessment (RA), and Life Cycle Assessment (LCA), distinctions need to be drawn between the purposes of each. EIA originated in the USA in 1969, as a result of the National Environmental Policy

Act (NEPA), which required that all major Federal actions be preceded by a systematic environmental analysis (Vigon, 1997b). The purpose of an EIA is to understand the possible environmental ramifications of a project before it is implemented, so that mitigation measures can be implemented.

RA began in the USA shortly afterwards in the 1970s, to address human health concerns regarding cancer. It has since evolved, and its present purpose is to quantify the likelihood and risk of a potential or actual adverse effect on human health or the environment (Vigon, 1997b). The main differences in data treatment with LCA, as opposed to RA and EIA, are the functional unit basis and allocation procedures used in LCA, as well as in the system boundary used.

1.3) THE STRENGTHS AND WEAKNESSES OF LCA

Some of the strengths of a LCA are that it:

- can provide an overview of complete systems
- identifies critical aspects of the life cycle
- highlights data deficiencies
- provides guidelines for actions
- increases awareness of environmental issues
- encourages comprehensive and global thinking
- provides an information base
- evaluates the overall material and energy efficiency of a system
- identifies pollution shifts between operations and media
- stimulates inter- and intra-company communication and co-operation (Jönson, 1996).

LCA also provides a multimedia perspective, in that different environmental media (air, water and soil) are considered (Barnthouse, 1998). In this manner, LCA aids in the attainment of a company's environmental objectives and targets. It must be noted, however, that LCAs can only provide a partial answer, as no one tool is able to cover all aspects of environmental management, and thus LCAs have a number of limitations (although many of them are not unique to LCA), including the following (Jönson, 1996):

- As a LCA relates to a specific moment in time, it provides a 'snapshot' view of the environmental impacts.
- The quality of the study is limited by the data available, and the validity of any assumptions made.
- The evaluation of the results may be difficult.
- Potential and not actual effects are considered.
- Evaluations that are subjective may be included.
- LCA studies require a great deal of work, and therefore incur time and monetary costs.
- There is currently a lack of relevant public databases, (especially for applications which have not previously been explored by LCA).

1.4) APPLICATIONS AND USES OF LCA METHODOLOGY

The applications of LCA include the areas of innovation, information, regulation and policy strategies, although LCA has primarily been used to date in the comparison of consumer products. Notably, the plastics and packaging industries have used LCA methodology quite extensively. The paper industry has provided a good example of how LCA can be used to reveal the differences between waste management policies in a clear and transparent manner (Daae and Clift, 1994). This example (a comparison of the alternatives of recycling and burning waste newsprint), also demonstrated that the Best Environmental Option (BEO) depends on the local circumstances, when sustainability (of fibre production in this example) is considered.

LCA is also proving to be a powerful tool in other processing industries (for example, ICI has successfully utilised a LCA-based approach, which will be discussed later; ICI, 1997a), as it addresses environmental impacts in the areas of ecological damage, human health effects and resource depletion, although other consequences of manufacturing activities, such as social and economic effects are not included (Perriman, 1993). It is for this reason that LCA cannot be used in isolation when decisions regarding product or process changes are made. Stand-alone, comprehensive LCAs may also be insufficient or inappropriate for the following reasons: those making the decision may not consider the environmental impacts assessed in LCA as being relevant to the decision at hand; the cost of

performing a LCA may outweigh the usefulness of the results; and the strategic context of the decisions (such as long term implications) are usually not considered in a LCA (Cowell, *et al*, 1997).

"Effective communication and evaluation of environmental information and the integration of this information with cost, performance, cultural and legal criteria will also be critical to the success of design initiatives based on the life cycle framework" (Keoleian, 1993). Often these factors are governed by local considerations, thus there is no single global solution (Vigon, 1998c). LCA can, however, be used as a decision support tool in environmental management, two examples being in the development of reuse and recycling strategies, and in assessing options for waste management (Udo de Haes and Huppes, 1993b).

Non-governmental organisations (including various 'green' groups) have noted that LCA can play the important role of encouraging new perspectives and uncovering hidden causes of environmental problems, by prompting new questions (Elkington, 1993).

LCA is a significant aspect of the European Union's Eco-Labelling criteria, and it plays an important role in the development of Environmentally Preferable Products, although Clift (1993b) has identified a number of problems associated with the use of LCAs for eco-labelling purposes. These include the vast differences in product types within the same product categories, which leads to difficulties in functional unit choice. The products are also made in different countries, which have different energy resources and waste disposal practices, thus a definition of "cradle" and "grave" becomes obscure. Decision-making is also difficult, as products can score differently on various environmental aspects.

The LCA Advisory Group of SETAC have a vision statement which is based upon the integration of life-cycle environmental criteria into an organisations' decision-making processes, thereby improving performance and demonstrating environmental progress (Vigon, 1997d). The simplified category indicators which LCA generates may be used as the basis for making comparisons, considering improvement opportunities, or to identify problem areas for further detailed investigation (Barnthouse, 1998).

The internal company applications of LCA may thus be summarised as: (Fava, *et al*, 1993)

- The establishment of a comprehensive baseline of information regarding overall resource and energy requirements and emissions produced.
- The identification of points within the process where the greatest reduction in resource requirements and emissions may be achieved, thereby increasing profitability.
- The comparison of the inputs and outputs associated with alternative processes, thereby aiding in new process development.

It is the opinion of some LCA practitioners that the information generated by an LCA should be used for analysis and assessment, never as a justification, however, as it is impossible to make an absolute statement about the environmental acceptability of a product. Thus statements such as "this product only contributes 1% to the depletion of the ozone layer" is regarded as being unacceptable (Heijungs, 1992b).

The broad approach of LCA also has the potential to assist in risk assessment, although there are limitations to its use, as the aggregation of emissions into effect scores may also conceal detail required in risk assessment. LCA provides a worst case scenario in that it implies that all emissions occur at sites which are sensitive to the substance concerned. In this manner, the relevancy of emissions is questionable, as only a zero emission would have a zero impact in an LCA context, and all theoretically possible consequences are considered. Details regarding duration, frequency and magnitude of average exposures are lost, as is the existence of any peak exposures. LCA may, however, provide valuable information for environmental assessments with respect to identifying pollution shifts between media (for example, from air to water) or operations (Owens, 1997a).

A number of policies and regulations relating to taxation on pollution, have been based on LCA studies, such as, the French tax on carbon dioxide emissions, and the Belgian and Norwegian packaging taxation programmes (Azapagic, 1997). Such approaches are also being encouraged by the EPA in the USA.

In ICI's 1997 Environmental Report, the targets with respect to environmental improvements are given as part of their SHE (Safety, Health and Environmental) Challenge 2000 programme (ICI, 1997a). The following targets are to be reached

by the end of the year 2000: energy efficiency per tonne of production is to improve by 10% with respect to the 1995 base level. In addition, the environmental burdens of ICI's operations world-wide are to be halved as compared to the 1995 baseline, (with respect to ecotoxicity, aquatic oxygen demand, acidity and potentially hazardous emissions (carcinogens) to air). This initiative followed on from ICI's development of an "Environmental Burden" (EB) approach based on LCA methodology, which was verified by an independent scientific panel (ICI, 1997b). This approach will now be discussed in some detail, as it provides an example of how a LCA-type approach has been used successfully in industry.

In this EB approach, impact categories were selected so as to concentrate upon those which were most significant to ICI's activities, and which they were most capable of improving. These categories are: acidity, global warming, human health effects (based solely on carcinogenicity), ozone depletion, photochemical ozone (smog) creation, aquatic oxygen demand, and ecotoxicity to aquatic life. With the exception of external energy generation, the approach currently excludes upstream and downstream operations (although these may be included at a later stage).

The EB approach utilises potency factors (similar to LCA classification factors) derived from different information sources, to calculate the EB associated with each problem category. The potency factors for human health effects are, for example, derived from Occupational Exposure Limit (OEL) values, with benzene being used as the reference substance (carcinogen). Environment Quality Standards (EQS) form the basis for aquatic ecotoxicity potency factors, thus only those releases which have been ascribed an EQS are included. Wastes to landfill are reported as tonnages, grouped as hazardous and non-hazardous waste. Impacts relating to landfill operations (emissions and leachate generation) are excluded due to the current lack of scientific knowledge in these areas. The different units of each EB meant that a total overall EB could not be calculated.

It is emphasised that the EB values relate to the full potential of ICI's emissions to cause environmental damage, and as such are conservative as degradation and other attenuating factors post-release are not considered. By means of the EB approach, ICI can identify the most harmful emissions by a ranking system, and then concentrate on reducing them. It also helps the public to understand the reasoning behind the company's environmental management strategy. A similar

approach to ICI's EB approach has also been adopted by the Dow Chemical Company.

With respect to base metal refiners, a number of LCA studies have been initiated, although many of these have been conducted for internal use by the company concerned, and the details and results of the studies have not been published. A cradle-to-gate Life Cycle Inventory of the Kristiansand Nickel Refinery of Falconbridge was compiled in 1997, in consultation with the University Stuttgart IKP (Morris, 1998a). The preliminary report thus generated is still under review and the information has not been released to the public as yet. The possibility of extending the study to other operations of Falconbridge is also under discussion. The impact categories which were considered in the Kristiansand study were global warming potential, acidification potential, and human toxicity (Morris, 1998b).

The Nickel Development Institute (NiDI), is presently preparing to perform a cradle-to-gate LCA exercise for generic metallic nickel, nickel oxide, and ferro-nickel, in conjunction with a consultant. In order to do this, data from over thirty mines, thirteen concentrators, eleven smelters, and thirteen refineries will be collected. The pyrometallurgical and hydrometallurgical processing of both lateritic and sulphidic ores will be incorporated into the results, of which only the overall LCI will be published. The exercise is being undertaken in order to support the sales and marketing of nickel products, to support the Environmental Management Systems of the participating companies, to identify opportunities for process improvement, to establish benchmarks of environmental performance, and to improve data on environmental indicators (McKean, 1998).

Some degree of standardisation of the methodology and data sourcing in LCA studies is necessary for public and peer confidence in them. The incorporation of LCA within the ISO 14000 framework is currently in progress, which should increase replicability and comparability, as there is presently significant potential for manipulation or abuses in the way LCAs are conducted, presented and applied. Transparency is therefore crucial and peer review is invaluable. Thorough explanation and justification of all assumptions and methodologies must be included. Confidence ranges of results and the implications of data deficiencies should also be discussed. It must be remembered that "indiscriminate distribution of

LCA studies is seldom appropriate, and can lead to damaging misinterpretation or misuse of the study results" (Denison, 1993).

It is therefore apparent that Life Cycle Assessment methodology has the potential to be a useful environmental management tool in the base metal refining industry, although the inherent limitations of the method must be borne in mind when drawing conclusions.

Chapter 2: PROCESS REVIEW

2.1) INTRODUCTION

This chapter reviews base metal refining technology, primarily as a backdrop for this study into the application of LCA methodology to the base metals industry. A general introduction to the various base metal refining processes is given in Section 2.2, in order to provide an overview of the industry and to highlight differences and similarities between technologies. The overall operations of Impala Platinum Limited Refineries are then discussed (Section 2.3), followed by a more detailed account of the chemistry of the Impala Base Metal Refinery (Section 2.4). This refinery will then form the focus of the study into the potential use of LCA in the base metals refining industry.

2.2) A REVIEW OF BASE METAL REFINING TECHNOLOGIES

The world's land-based nickel bearing ores are of two types: sulphidic and lateritic. The sulphide ores account for approximately 55% of the world's current nickel production, and the laterite ores for the remaining 45% (Anthony, *et al*, 1997). Although nickel is also present in nodules on the ocean floor (as discovered by the H.M.S. Challenger expedition between 1872 and 1876) (Kohga, *et al*, 1996), this source has not been utilised to any significant extent for economic reasons.

Due to inherent differences in the geological and mineralogical characteristics of the laterite and sulphide ores, different methods are employed in their mining and extractive metallurgy. The processing of laterite ores is, for example, dominated by energy usage, whereas sulphidic ores release exploitable energy during smelting operations (Anthony, *et* al, 1997). Sulphide ores associated with precious metals are mined and processed in South Africa. It is the various technologies which are currently available for the treatment of mattes generated from the smelting of such ores which will be discussed in this section.

The earliest production of nickel was from the arsenical sulphide ores found in Europe (Simons, 1988). The commercial exploitation of laterite deposits in New Caledonia began in 1875, followed by the processing of sulphide deposits located in the Sudbury Basin in Ontario, Canada in 1885 (Anthony, *et al*, 1997). These operations required the development of processes to separate metals found in conjunction with nickel. The Orford

Copper Company of the United States of America, for example, employed the physical separation of the upper copper-iron layer from the nickel sulphide bottom layer, produced upon cooling the molten matte, when mixed with coke and sodium sulphate. This **Orford Process** was first used commercially in 1891 (Simons, 1988).

Around this time, Ludwig Mond of England discovered that a nickel-bearing gas could be formed by passing carbon monoxide over finely divided nickel metal. He developed this observation into the **Mond Process**, which was able to produce nickel of higher purity. The disadvantages of this process were the high toxicity of the nickel carbonyl gas, the slow reaction kinetics, and the large gas volumes. Nevertheless, this process has been exploited commercially by **INCO** (Figure 2.1).

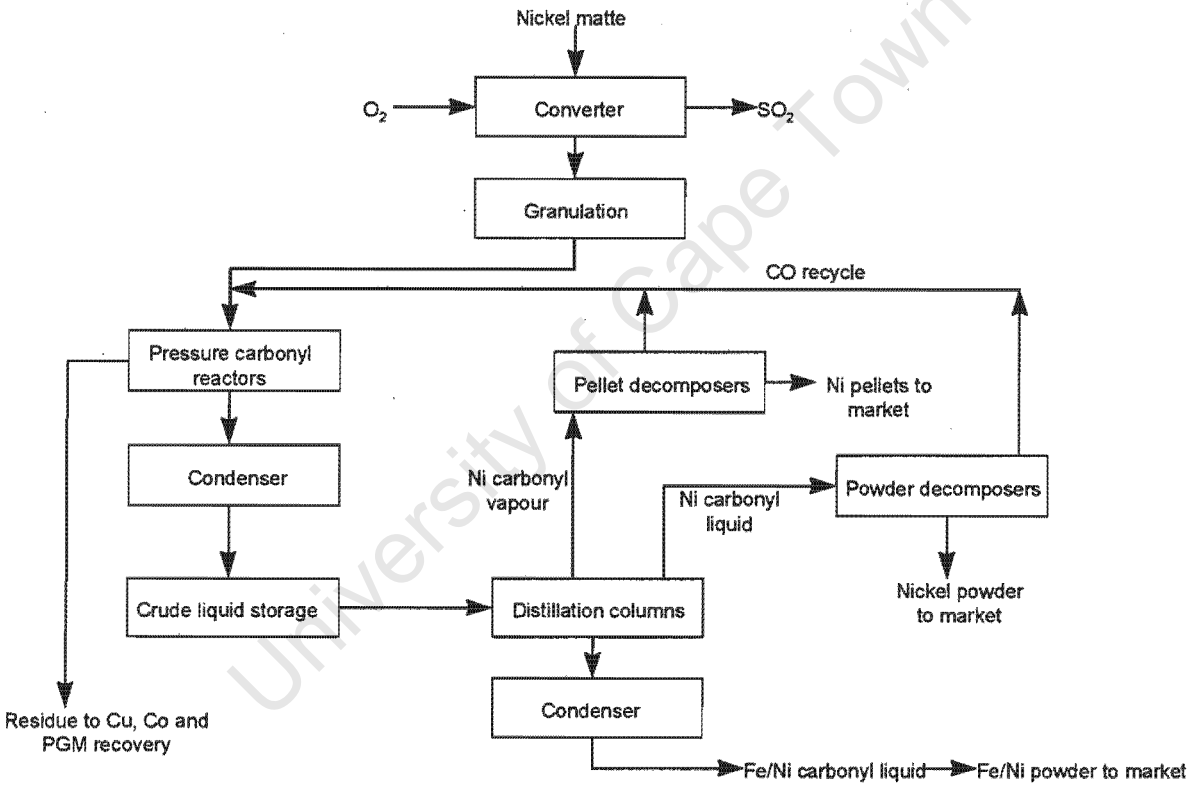


Figure 2.1: INCO carbonyl nickel matte refining flowsheet (Anthony and Flett, 1997).

The electrolytic refining of sulphide mattes, leached with dilute sulphuric acid, was developed by the Swede, N.V. Hybinette in the 1890's (Simons, 1988). The advent of the First World War brought about a boom in the nickel market, which resulted in many new nickel ventures. Once the demand for nickel from the military had abated, civilian applications were developed to boost the flagging industry. Soon hydrometallurgy (extraction of metals by chemical dissolution), became the dominant means of extraction (Boldt, 1967).

A number of factors govern the choice of leaching reagents for these processes. These include cost, ability to selectively leach metals, ease of spent reagent recovery, and the corrosivity of the reagent (with respect to process equipment). The relationship between temperature and solubility is also exploited, in order to enhance separations of metals based on their differences in solubility (refer to Impala's Co/Ni separation process (section 2.4.3), for example). Leaching rates are determined by a number of factors, including the reagent concentration, matte particle size (and therefore surface area), temperature, pressure, and agitation rate.

A number of different hydrometallurgical applications currently in operation will now be discussed.

Sherritt International Corporation is a Canadian metal mining, refining and manufacturing company, which has developed pressure hydrometallurgy technology for application in nickel and cobalt refining. One of the advantages of this type of processing is that it eliminates the problem of sulphur dioxide emissions during metal sulphide leaching, as saleable sulphur-containing by-products, such as ammonium sulphate, can be produced. Pressure hydrometallurgical processes can also be readily automated.

The first Sherritt process was developed between 1948 and 1953, and resulted in the construction of a nickel refinery at Fort Saskatchewan, Canada in 1954 (Mackiw and Veltman, 1982). This process is based on an ammoniacal ammonium sulphate pressure leach (to form soluble nickel ammines), followed by nickel metal recovery as powder upon hydrogen reduction of the solution. The concentrate treated at this facility typically contains 10% Ni, 0.5% Co, 2% Cu, 38% Fe, 31% S, and 14% gangue (Boldt, 1967). Horizontal, multi-compartment autoclaves are employed for the leaching process, and are positioned in a two-stage countercurrent arrangement. Feed slurry is pumped continuously into one end of the autoclave and cascades from one compartment to the next over v-notch weirs (Veltman and Weir, 1981).

The acid pressure leaching of nickel-copper matte was developed by Sherritt Gordon in the late sixties, and is employed by a number of South African precious metal producers, which refine base metals as by-products. These include Impala (established in 1969) (refer to Figure 2.2), Rustenburg Refiners (in 1982), and Western Platinum (in 1985).

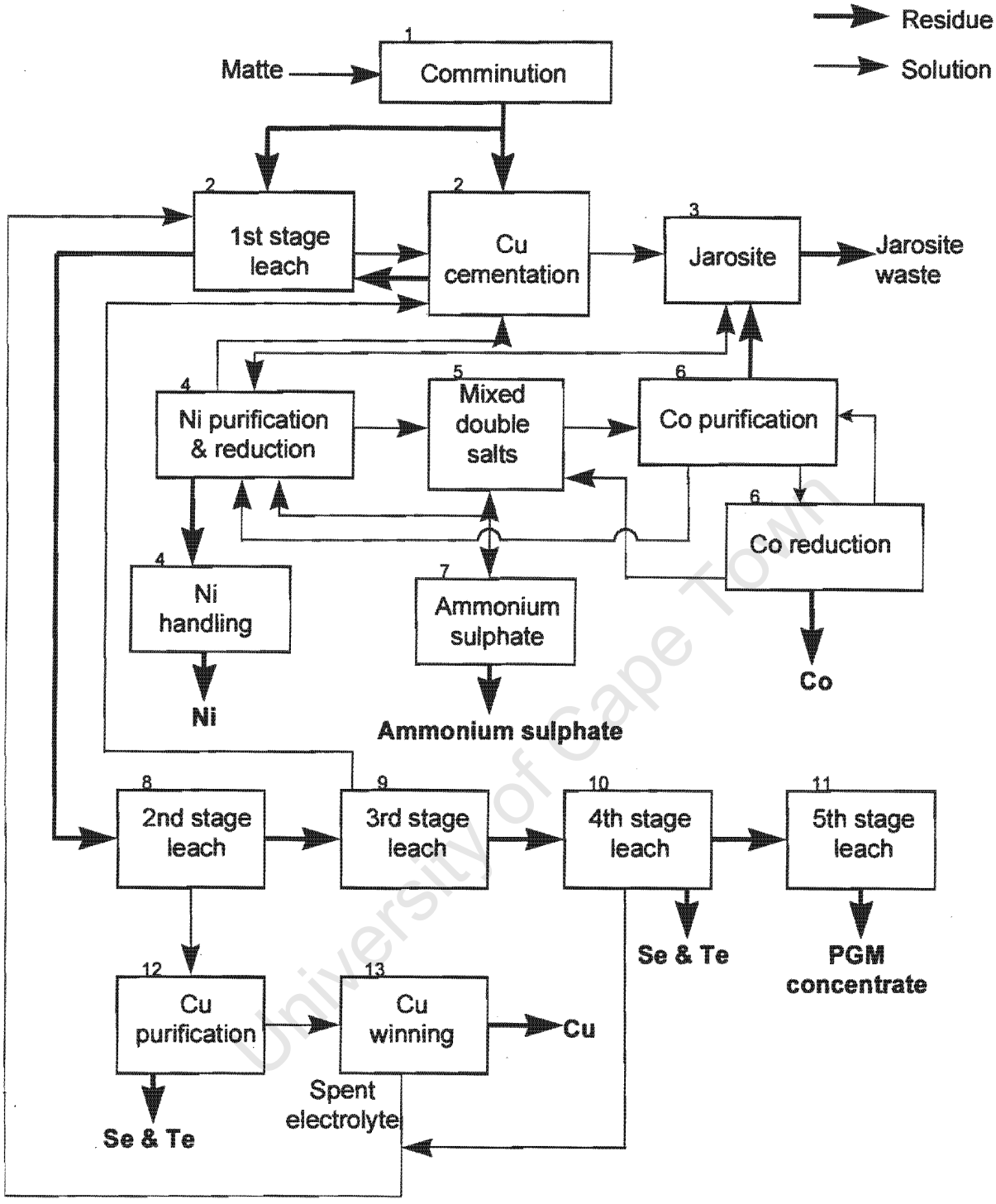


Figure 2.2: Impala Platinum Ltd Base Metal Refinery flowsheet.

The matte treatment flowsheets differ significantly at each of these refineries, in order to meet specific product requirements, and to be integrated into existing operations. The Impala flowsheet is discussed in detail in Section 2.3. At **Rustenburg Refiners**, a non-magnetic nickel-copper matte is obtained by means of a slow cooling matte separation process. Nickel and copper are separated from this portion by means of an atmospheric

and two pressure leach stages, and are then recovered electrolytically, as shown in Figure 2.3. Nickel-spent electrolyte is neutralised with sodium hydroxide, in a sulphur removal step, to produce sodium sulphate (Hofirek and Kerfoot, 1992). Solvent extraction (utilising di-(2-ethylhexyl)phosphoric acid (DEHPA)) is employed to purify the cobalt cake (Burks, 1997), obtained from the Outokumpu Base Metals Oy cobalt removal process (for details refer to Figure 2.6). The small quantities of Precious Group Metals (PGMs) contained in the non-magnetic matte are recovered in an iron oxide leach residue, which is recycled to the smelter (Brugman and Kerfoot, 1986).

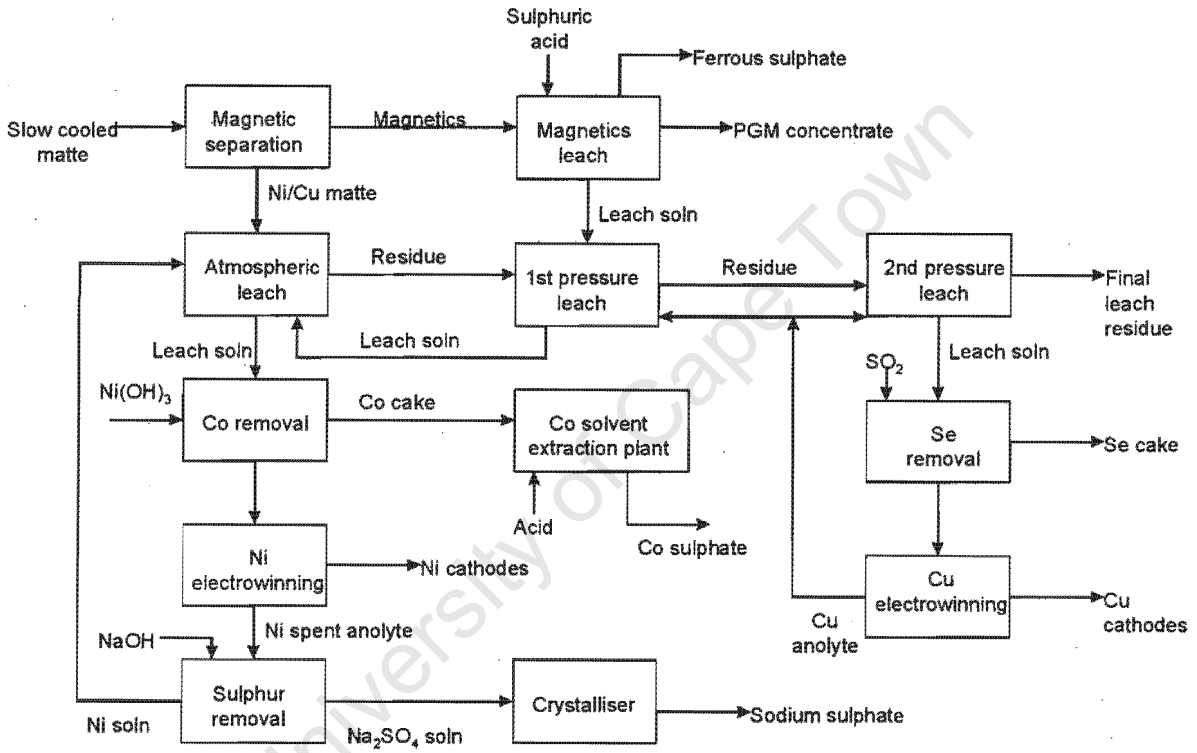


Figure 2.3: Rustenburg Base Metal Refinery flowsheet (Hofirek and Badcock, 1997).

Western Platinum utilises an atmospheric first stage leach to provide a relatively pure, high-concentration nickel sulphate solution, from which nickel sulphate hexahydrate is crystallised (refer to Figure 2.4). This material is sent to toll refiners (including Impala) for further purification. Although the nickel extraction efficiency is reduced due to operation at atmospheric pressure, precipitation of copper and PGMs is enhanced, resulting in a purer nickel solution leaving the initial leach. A high temperature second stage pressure leach is then used to leach nickel and copper, and thereby a PGM concentrate is produced. Nickel contamination of the copper cathodes is prevented by operating at low current densities,

and selenium is removed from this copper stream by treatment with sulphur dioxide (Brugman and Kerfoot, 1986).

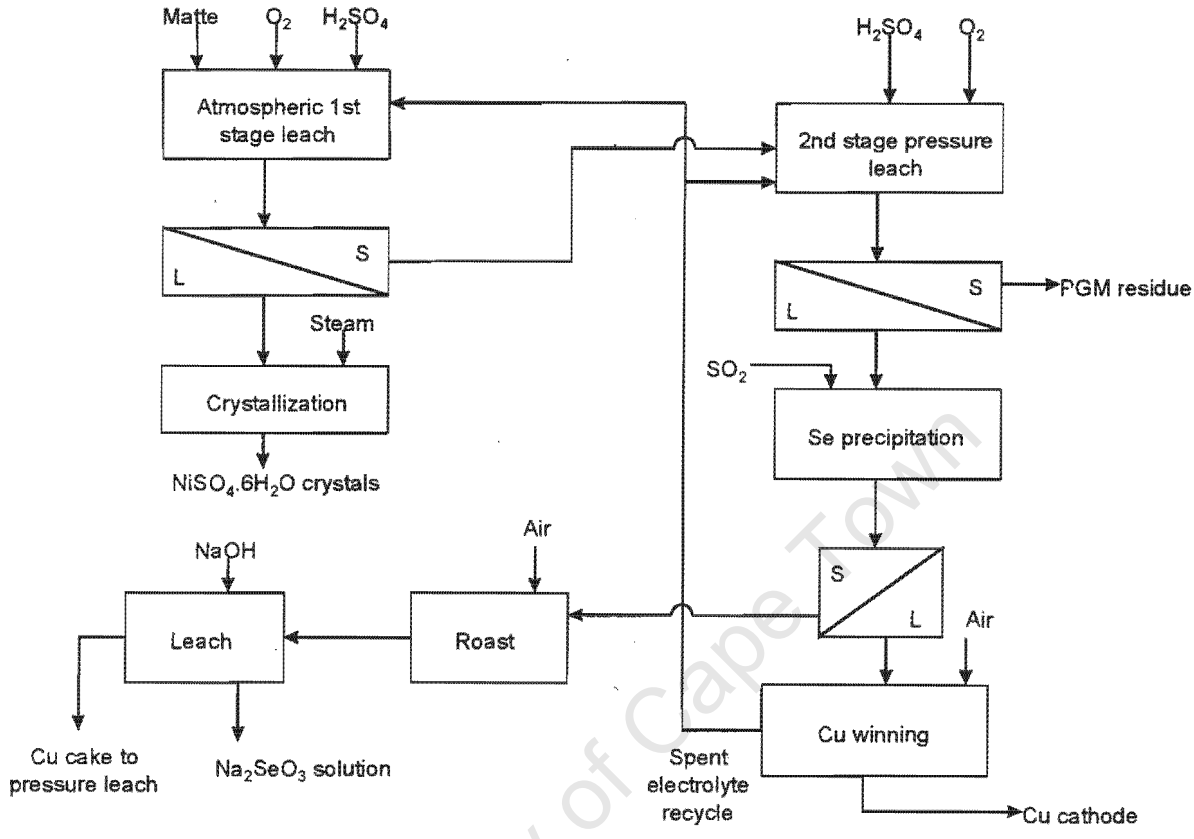


Figure 2.4: Western Platinum Base Metal Refinery flowsheet (Brugman and Kerfoot, 1986).

Technologies for the recovery of nickel and cobalt from lateritic ores, and copper from copper sulphide concentrates have also been developed by Sherritt Gordon (Mackiw and Veltman, 1982).

In addition, Sherritt have developed a cobaltic pentammine process, for application in cobalt refining, which is used in Finland and in part by Impala (Mackiw and Veltman, 1982). Processes to separate nickel and cobalt were developed following the requirements for high purity nickel stainless steels, with minimal cobalt contamination, for nuclear reactors in the 1950's (Simons, 1988). This was due to the fact that the natural cobalt isotope (^{59}Co) can be converted, by neutron capture, to the gamma and beta ray emitting ^{60}Co isotope, which has a half life of over five years. Thus any irradiated stainless steel containing cobalt would pose a serious health risk. There was also a new market for high purity cobalt for use in jet engines, for example (Simons, 1988).

Solvent extraction is another technique employed in nickel/cobalt separations (and is used at Rustenburg Refineries). These processes are generally based on selective ion-pair formation or coordination chemistry, to facilitate selective extraction. The **Hartley Platinum** base metal refinery, situated in Zimbabwe, utilises the organophosphinic acid, Cyanex 272 (Figure 2.5). This extractant removes cobalt and impurities (primarily zinc and lead), leaving a relatively pure nickel sulphate solution. The cobalt sulphate strip solution is neutralised with sodium carbonate, and the crude cobalt carbonate precipitate is toll refined. After the nickel has been electrowon, a portion of the anolyte is neutralised with sodium carbonate, to precipitate residual nickel as nickel carbonate. Sodium sulphate is then crystallised from the nickel-free solution (Montgomery and Holohan, 1997).

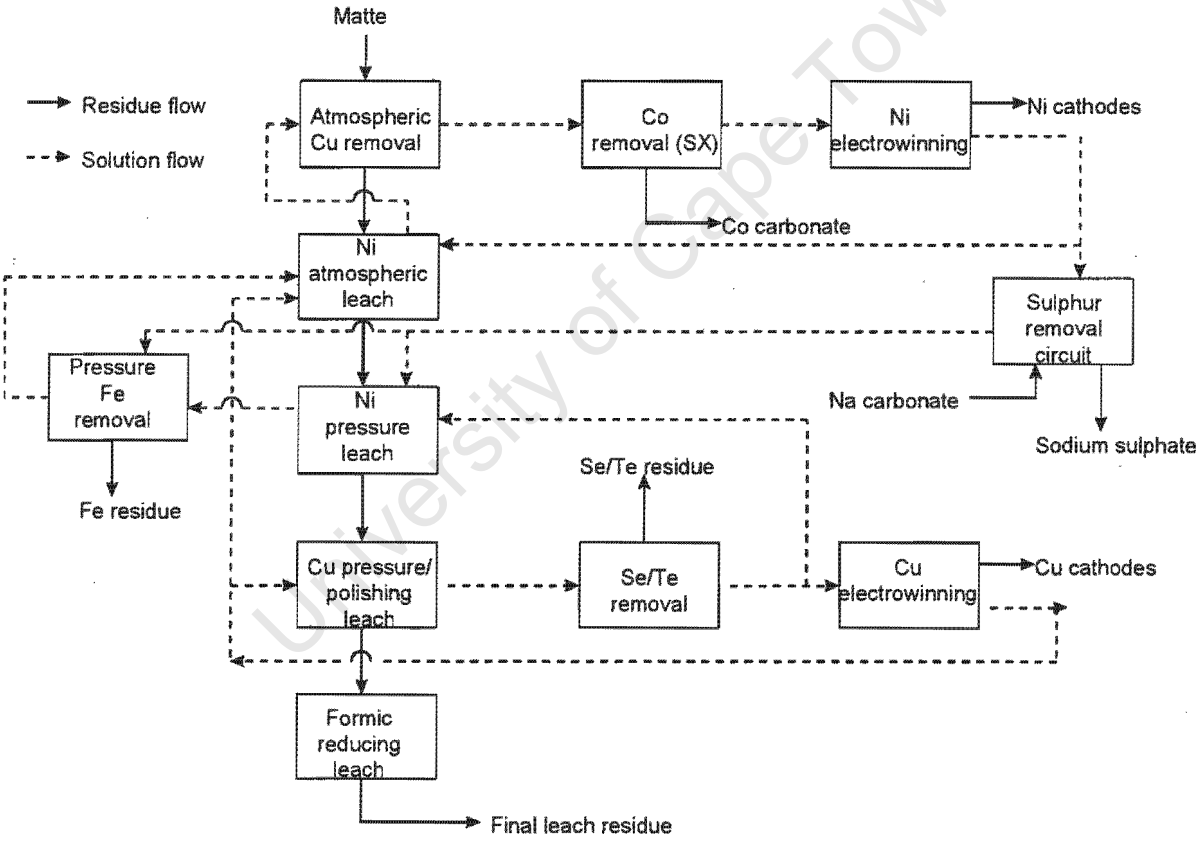


Figure 2.5: Hartley Platinum Base Metal Refinery flowsheet (Montgomery and Holohan, 1997).

Oxidation processes for cobalt removal currently being investigated include oxidation using ammonium persulphate, Caro's acid (generated from hydrogen peroxide and concentrated sulphuric acid), and ozone (Burks, 1997). It has been stated with respect to cobalt

extraction, however, that "for optimal processing for both high recovery and selective removal, solvent extraction is easily the best process" (Flett, 1987).

The original **Outokumpu** nickel process involved the electrowinning of copper and nickel from sulphate solutions produced from the sulphuric acid leaching of mattes (Figure 2.6). Lead was removed from the leach solution prior to nickel electrowinning by the addition of barium hydroxide. Cobalt was also removed from the solution by precipitation as Co(III) hydroxide, using Ni(IV) hydroxide produced electrolytically from Ni(II) hydroxide (Outokumpu, 1993). This also served as a scavenging step for other impurities (Burks, 1997). Cobalt solvent extraction is now employed, and the cobalt and a portion of the nickel which is not electrowon, are recovered by hydrogen reduction. Other changes include an atmospheric leach which is followed by a pressure leach, and sulphur recovery as ammonium sulphate (Outokumpu, 1995).

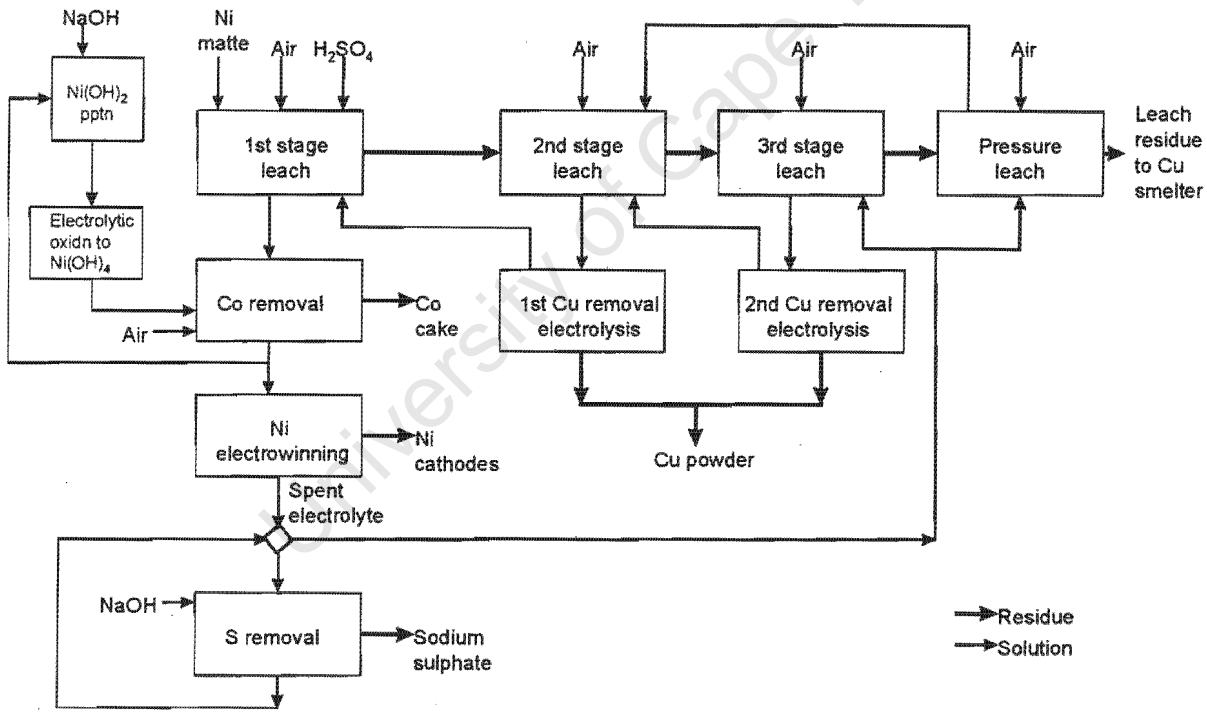


Figure 2.6: Outokumpu Base Metal Refinery flowsheet (Burkin, 1987, and Burks, 1997).

The **Falconbridge** matte leach process involves chlorine/hydrochloric acid leaching (refer to Figure 2.7). The hydrogen sulphide which is produced prevents copper dissolution. Solvent extraction purification is then performed on the nickel/cobalt solution. The metals (including copper) are recovered electrolytically (Stensholt, *et al*, 1985).

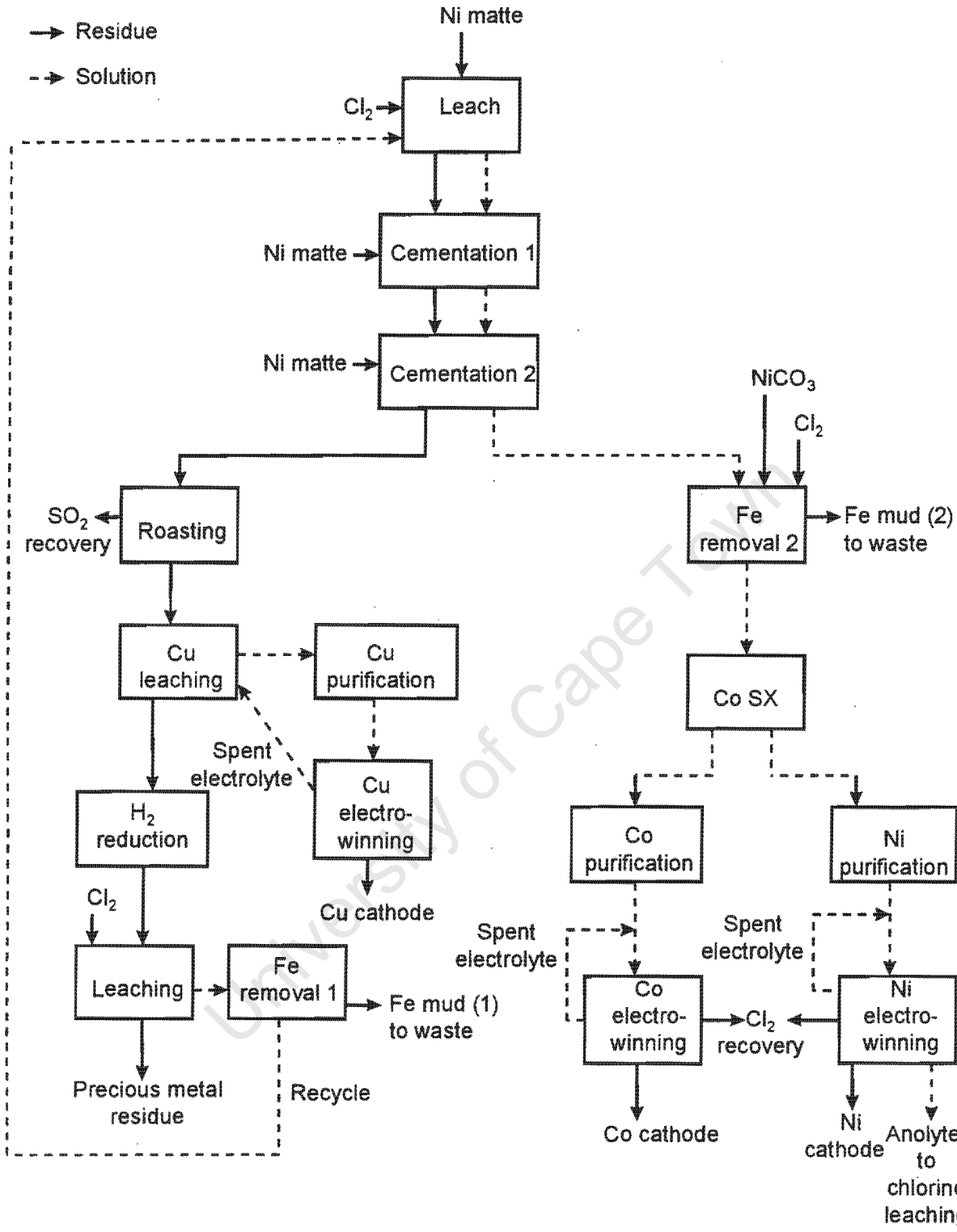


Figure 2.7: Falconbridge Base Metal Refinery flowsheet- Electrowinning option (Burkin, 1987).

Other mining companies have developed similar processes, for example **Sumitomo Metal Mining Company Limited**. Their process involves the extraction of cobalt and nickel with a

tertiary carboxylic acid, in order to facilitate a chloride based solvent extraction separation by tri-n-octylamine (TNOA). This is followed by electrowinning of the nickel and cobalt chloride solutions thus generated, as shown in Figure 2.8 (Suetsuna, *et al*, 1980 and Inami, *et al*, 1984).

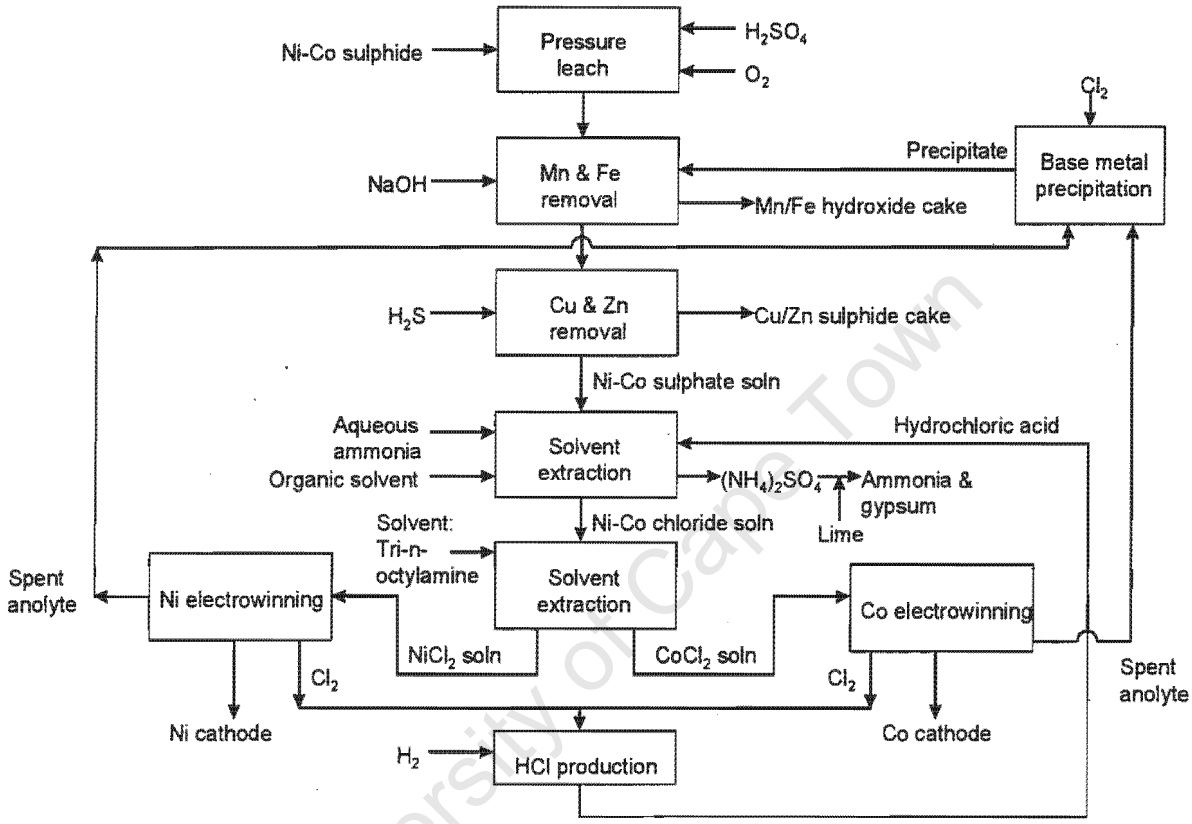


Figure 2.8: Sumitomo Niihama Nickel Refinery flowsheet (Suetsuna, *et al*, 1980, and Burkin, 1987).

It is evident that matte treatment is a complex process with technology choice based on a number of factors such as matte composition, geographical situation and the cost of proprietary technologies. The operations of Impala Platinum Limited will now be discussed in detail.

2.3) AN INTRODUCTION TO THE OPERATIONS OF IMPALA PLATINUM LIMITED

Union Corporation announced its intention to establish a platinum mine near Rustenburg on September 15, 1967, after extensive prospecting and market studies. Consequently Impala Platinum came into being, with the first matte being pumped into the autoclaves at the Refineries complex on 1 July 1969 (Ireland, 1979).

The Rustenburg mining operations are situated on the Western flank of the Bushveld Complex, where the composite band of ore, known as the Merensky Reef is mined. Platinum minerals were first discovered in 1924 by a farmer, Andries Lombaard, in the Lydenburg district of the present Mpumalanga. These were identified as bearing platinum by Dr Hans Merensky. He also predicted and proved the presence of platinum-bearing rock in the Potgietersrus and Rustenburg areas.

The Merensky Reef is a sheet-like body approximately 1m thick, which occurs in a layered suite of igneous rocks referred to as the Critical Zone of the Bushveld Complex (Impala Platinum Limited, 1982). The mineralisation in the Merensky Reef occurs as base metal sulphides (pyrite, pyrrhotite, pentlandite and chalcopyrite), with associated precious metal minerals (including braggite, cooperite, laurite and sperrylite) (Ireland, 1979).

The Merensky Reef has a reserve base of 21100t of platinum-group metals, 6.4Mt of nickel, 3.9Mt of copper, and 8500t of cobalt, where the reserve base includes those resources which are currently economic and those which are marginally economic. (Van Graan, 1992). Subsequently mining of another lower grade reef, known as the UG-2 Reef, commenced in 1973, in order to increase production and meet the increasing demand for platinum. This reef is situated approximately 50 to 150m below the Merensky Reef, and thus could be relatively readily accessed without major capital expenditure (Gaylard, 1998a). This UG2 Chromitite Layer has a reserve base of 31400t of platinum-group metals, 3.0Mt of nickel, 2.7Mt of copper, and 3500t of cobalt (Van Graan, 1992).

The mined ore is transported by rail to Mineral Processes (MinPro) in Rustenburg, where the ore is upgraded by a sequence of metallurgical processes. Firstly, the ore is milled to decrease the particle size, to allow for the liberation of the valuable minerals by flotation. The mineral-laden froth overflows from the flotation cells as a concentrate, which may be upgraded in 'cleaner' flotation cells. The barren slurry is pumped to a tailings dam. This

process increases the grade of the valuable material approximately forty-fold. However, only around 80-90% of the mineral content is recovered, making this step the most inefficient in the whole metallurgical process. The future challenge with flotation is to increase selectivity without compromising metal recovery.

The final flotation concentrate is further upgraded in a smelter, to separate entrained gangue particles. After dewatering in thickeners, the concentrate is spray dried in a stream of hot air created by burning coal. The concentrate is then mixed with fluxes and is fed into electric furnaces, where the molten furnace matte separates by gravity from the molten gangue or slag. The furnace matte, containing the base and platinum-group metals (PGMs), is transferred to Pierce-Smith converters. The furnace slag is granulated in water as it is tapped from the other end of the furnace. Up until 1994, this slag was disposed of on a dump. It is now taken to a slag retreatment plant, where it is milled and then floated to recover the remaining PGMs, which are then returned to the smelter. In addition, slag from the dump is being re-processed in this manner. Tailings from the slag retreatment plant are routed to the tailings dam (Gaylard, 1998a).

The sulphur dioxide, which is produced from the decomposition of the sulphide ore in the smelter, is converted to sulphuric acid to reduce emissions. The sulphuric acid is sold to a facility which produces phosphoric acid for the fertiliser industry.

Iron, which interferes with the refining process, is largely removed from the matte in Pierce-Smith converters, where the matte is fluxed with silica and air is blown through it. Excess sulphur is thereby removed as sulphur dioxide and the converter slag contains most of the iron. This is returned to the furnace, to be ultimately disposed of with the furnace slag. The converter matte, containing approximately 50% nickel, 28% copper, 20% sulphur and 0.3% PGMs, is granulated in water, and transported to the refinery in Springs by road and rail. At this stage the material has been concentrated approximately 1000 times with respect to the precious metals, relative to the original mined ore.

The refinery complex is based in Springs for a number of reasons. Firstly, the surface installations were present from the East Geduld Gold Mine, which previously occupied the site. In addition, the presence of the research laboratories of the Union Corporation Group provided technical assistance during commissioning. The availability of experienced labour and Sasol gas in the Springs area, as well as its proximity to Johannesburg International

Airport for export of precious metal products, were other contributory factors (Impala Platinum Limited, 1989).

Upon its arrival in Springs, the matte is processed by the Base Metals Refinery (BMR). It is this section of Impala's operations which were studied in this project. A brief overview of the processes as shown in Figure 2.2 will therefore be given here, which will be expanded on later in Section 2.4.

The matte is first milled in ball mills with water, to increase the available surface area and so allow for the efficient extraction of the base metals. The slurry thus produced is treated according to the Sherritt Gordon acid pressure leach process. In the first stage leach, nickel and cobalt are selectively dissolved from the matte under oxidising acidic (sulphuric acid medium) conditions accompanied by high temperatures and pressures. Any dissolved copper is removed from the solution by cementation reactions in the final reducing compartments of the autoclaves and by subsequent matte addition. Iron is removed from the solution by means of jarosite precipitation, which is disposed of to landfill (Montgomery and Holohan, 1997).

After conversion to the ammine form, the nickel is reduced with hydrogen. The nickel powder thus produced is sold as such, or is briquetted. Some of these briquettes are then sintered to remove carbon and sulphur impurities. The remainder are sold in the unsintered form.

Mixed double salts of nickel and cobalt are precipitated from the reduction end solution. A portion of the neutralised filtrate is recycled to the nickel purification circuit and the remainder evaporated to form ammonium sulphate crystals, which are sold as fertiliser.

After dissolution of the nickel and cobalt mixed double salts, residual impurities (such as iron) are precipitated from the solution upon aeration. The cobalt is then oxidised to cobaltic pentammine and the solution is acidified and then cooled, in order to selectively precipitate the nickel double salt. This is then redissolved and returned to the nickel circuit. Cobaltous ammine complexes are formed from the remaining solution upon addition of recycled cobalt powder. The cobalt is then reduced to cobalt powder with hydrogen.

The copper is dissolved from the first stage solid residue in the second stage leach, which employs more severe leaching conditions than the first stage. Selenium and tellurium are

leached together with the copper, but are mostly re-precipitated with sulphur dioxide and are processed by toll refiners. The copper is then removed from the solution by electrowinning and the resulting copper cathodes marketed. The sulphuric acid which remains is recycled to the first stage leach. The Isa Process is used for copper electrowinning at Impala. Permanent stainless steel cathodes are recycled for continuous use and associated with this is mechanised electrode handling equipment, where automatic cathode stripping (including in-line sampling, weighing, labelling and bundling) has resulted in lower labour costs (Lang *et al*, 1997).

Iron, residual copper, selenium, tellurium and arsenic are further removed from the second stage solid residue during the subsequent leaching stages (third, fourth and fifth stage leaches). The resulting platinum group metal concentrate is then consigned for processing to the Precious Metals Refinery (PMR). Effluent generated by the BMR processes is currently re-used by another company in the recovery of slimes dams.

In the PMR the concentrate is dried and pulverised. A mixture of chlorine and hydrochloric acid is then employed to dissolve the precious metals. The leach residue is smelted or re-leached. A portion of the resulting smelt material is reprocessed and the remainder toll refined. Silver chloride is precipitated from the leachate, upon the addition of water, and is sent to toll refiners. Gold and palladium are recovered from the solution in series by ion exchange, which selectively extracts the specific metal. The metal is washed off the resin during the elution cycle, and reduced to the metal in the case of gold. The palladium is precipitated as a salt which is dried and ignited under reducing conditions to form a metal sponge (De Waal, 1997).

Base metals are then purged from the solution, by means of another ion exchange process. The base metal cake thus produced is sent to toll refiners. Ruthenium is recovered from the remaining solution by distillation. A hydrolysis step precipitates rhodium and iridium, which are then separated from each other by another ion exchange process, to produce the pure metals. The liquor remaining from the hydrolysis step is subjected to a bromate hydrolysis, and platinum is precipitated from the resulting solution. The solids are recycled to the primary leach step (De Waal, 1997).

The barren solutions which are produced in all these PMR processes, are treated to recover any platinum group metals. Solids thus generated are smelted to produce both a slag, which is returned to Mineral Processes, and an iron-based smelter matte, which is

presently toll refined. (Previously it was returned to the BMR for re-processing). The effluent remaining after treatment of the barren solutions is concentrated by means of an enhanced evaporation system, and further treated to remove traces of platinum group metals.

Numerous reagents are required in all of these processes. The Utilities section of the BMR and PMR serve to provide many of these, as well as other services. Hydrogen plants on the BMR site, for example, convert Sasol gas into hydrogen and carbon dioxide for use in the processes. In addition, Rand Water Board water is demineralised, steam is generated, and compressed air and vacuum are provided by the BMR Utilities section. These ancillary operations are discussed in more detail in Chapter 4.

2.4) THE CHEMISTRY OF IMPALA PLATINUM LIMITED'S BASE METAL REFINERY

Due to the fact that the operations of the base metal refinery, and its environmental performance were of interest in this project, the chemistry of the processes involved are now described in more detail. Reference is made to unit operations as given in the flow diagram of the BMR used in this study (Figure 2.2). The reasons for defining the unit operations in this manner are discussed in Chapter 4, Section 4.2.

2.4.1) Leaching

The matte is **milled** with water (unit operation 1). It is then mixed with acidic spent electrolyte from the copper electrowinning circuit resulting in an atmospheric pre-leach (Spandiel, 1997). The nickel alloy present in the matte reacts with the sulphuric acid and copper sulphate present in the spent electrolyte as follows:

$$Ni + Ni_3S_2 + 4CuSO_4 \rightarrow 4NiSO_4(aq) + 2Cu_2S \quad (1)$$

(Rademan, 1997)

$$2Ni + 2H_2SO_4 + O_2 \rightarrow 2NiSO_4(aq) + 2H_2O \quad (2)$$

(Brugman, and Kerfoot, 1986)

NiS is also produced upon reaction of Ni_3S_2 with copper sulphate or sulphuric acid and oxygen, as follows (Hofirek and Kerfoot, 1992):

$$2Cu^{2+} + Ni_3S_2 \rightarrow 2Ni^{2+} + NiS + Cu_2S \quad (3)$$

$$2Ni_3S_2 + 4H^+ + O_2 \rightarrow 4NiS + 2Ni^{2+} + 2H_2O \quad (4)$$

The matte slurry is then fed into the first stage autoclave, where an **oxidative leach** occurs in the first two compartments, in the presence of oxygen (unit operation 2). This leaching process, which was developed by Sherritt Gordon, dissolves the majority of nickel and cobalt from the matte. In addition to reactions (1) and (2), NiS is also oxidised during this stage to nickel sulphate and a new nickel sulphide, Ni_3S_4, rendering approximately 87% extraction of nickel (Brugman and Kerfoot, 1986):

$$8NiS + 2H_2SO_4 + O_2 \rightarrow 2NiSO_4(aq) + 2Ni_3S_4 + 2H_2O \quad (5)$$

$$NiS + 4H^+ + 3O_2 \rightarrow NiSO_4(aq) + 2H_2O \quad (6)$$

The copper is oxidised as follows (Plasket and Romanchuk, 1978):

$$2Cu_2S + 2H_2SO_4 + O_2 \rightarrow 2CuS + 2CuSO_4(aq) + 2H_2O \quad (7)$$

Iron acts as an electron carrier, as it is first oxidised, and then reduced upon reaction with a base metal sulphide, as given below, using nickel as an example (Hofirek and Kerfoot, 1992);

$$4FeSO_4(aq) + 2H_2SO_4 + O_2 \rightarrow 2Fe_2(SO_4)_3 + 2H_2O \quad (8)$$

$$Ni_3S_2 + Fe_2(SO_4)_3 \rightarrow 2NiS + NiSO_4(aq) + 2FeSO_4(aq) \quad (9)$$

Cobalt (present mainly as Co_3S_2) is similarly leached in the form of cobaltous sulphate ($CoSO_4$). Approximately 83% of Co is extracted in this first stage leach. Iron (approximately 73%), lead and manganese (almost 100%) are also extracted as their sulphates.

Iron in the form of FeAsS, reacts as follows:

$$4FeAsS + 6H_2O + 13O_2 \rightarrow 4H_3AsO_4 + 4FeSO_4(aq) \quad (10)$$

The third and fourth compartments of the first stage autoclave have a reducing environment, which is conducive to the cementation of copper (metathesis) at pHs below 3 (Plasket and Romanchuk, 1978):

$$CuSO_4(aq) + NiS \rightarrow CuS + NiSO_4(aq) \quad (11)$$

The absence of oxygen also prevents reaction (12) below from occurring, which would increase the copper concentration in the nickel solution. Approximately 48% of the matte is leached in this first stage.

$$CuS + 2O_2 \rightarrow CuSO_4(aq) \quad (12)$$

(Plasket and Romanchuk, 1978)

Approximately 98% of the copper is then extracted in the **second stage oxidative leach** (unit operation 8), according to reaction (12), as well as virtually all of the residual nickel and cobalt. Cuprous selenide and telluride are also leached in this stage, to form copper sulphate and the corresponding acids. The acids are then further oxidised:

$$Cu_2Se + 2H_2SO_4(aq) + 2O_2 \rightarrow 2CuSO_4(aq) + H_2SeO_3 + H_2O \quad (13)$$

$$Cu_2Te + 2H_2SO_4(aq) + 2O_2 \rightarrow 2CuSO_4(aq) + H_2TeO_3 + H_2O \quad (14)$$

$$2H_2SeO_3 + O_2 \rightarrow 2H_2SeO_4 \quad (15)$$

$$2H_2TeO_3 + O_2 \rightarrow 2H_2TeO_4 \quad (16)$$

Leaching of remaining lead and iron also occurs. Approximately 94% of the solids are leached during this second stage, thus only 3.1% of the matte reports to the third stage leach.

The **third stage pressure leach** (unit operation 9) is used to remove iron from the precious metals. The latter are also dissolved to some extent during this aggressive oxidative acid leach, thus a formate reductive step is used to re-precipitate these elements. Iron is reduced to the soluble ferrous sulphate, which is thereby separated from the PGMs:

$$2Fe_2(SO_4)_3 + 2NaHCO_2 \rightarrow 4FeSO_4 + H_2SO_4 + 2CO_2 + Na_2SO_4 \quad (17)$$

The **fourth stage oxidative leach** (unit operation 10) is used to remove residual copper from the PGM concentrate. Residual nickel and iron are also removed, as are trace elements such as selenium, tellurium and arsenic, via precipitation with sulphurous acid, as follows:

$$H_2SeO_3 + 2CuSO_4 + 4H_2SO_3 + H_2O \rightarrow Cu_2Se + 6H_2SO_4 \quad (18)$$

The resulting solution is routed back to the first stage leach with the spent copper winning electrolyte.

Selenium, tellurium and arsenic, along with sulphur are further purged from the PGMs during the **fifth stage caustic leach** (unit operation 11). The sodium hydroxide neutralises the sulphuric acid, while base metals (denoted M below) present in the slurry precipitate as hydroxides. Anionic complexes may form, however, which are soluble:

$$MSO_4(aq) + 2NaOH \rightarrow M(OH)_2 + Na_2SO_4 \quad (19)$$

$$M(OH)_2 + 2NaOH \rightarrow Na_2M(OH)_4 \quad (20)$$

Oxidation of any residual selenium and tellurium yields insoluble sodium salts:

$$2Cu_2Se + 4NaOH(aq) + 5O_2 \rightarrow 4CuO + 2Na_2SeO_4 + 2H_2O \quad (21)$$

Some silica dissolves as sodium *meta*silicate:

$$SiO_2 + 2NaOH \rightarrow Na_2SiO_3 + H_2O \quad (22)$$

Some PGMs dissolve in the form of anionic hydroxides and oxides, but later re-precipitate as the neutral compounds during carbon dioxide neutralisation treatment.

2.4.2) Nickel solution purification and reduction

The copper present in the first stage leach solution must be removed prior to nickel production so as to prevent contamination (unit operation 2). This is achieved by addition of matte to the solution. The nickel in the matte cements the copper, as in the first stage leach (reaction (1) and (3)). Sodium hydrosulphide is also used to aid with the **cementation of copper** as CuS.

Jarosite is precipitated from the resulting solution in order to remove iron (unit operation 3). The iron is oxidised to ferric sulphate in which form it reacts with ammonium sulphate to produce ammonium jarosite (Plasket and Dunn, 1986a):

$$3Fe_2(SO_4)_3(aq) + (NH_4)_2SO_4 + 12H_2O \rightarrow 2NH_4Fe_3(SO_4)_2(OH)_6 + 6H_2SO_4 \quad (23)$$

Arsenic and lead are also precipitated as follows (Plasket and Dunn, 1986a):

$$2H_3AsO_4 + Fe_2(SO_4)_3(aq) \rightarrow 2FeAsO_4 + 3H_2SO_4 \quad (24)$$

$$Pb^{2+}(aq) + SO_4^{2-} + 3Fe_2(SO_4)_3(aq) + 12H_2O \rightarrow 2Pb_{0.5}Fe_3(SO_4)_2(OH)_6 + 6H_2SO_4 \quad (25)$$

Ammonia is added to the autoclave to neutralise the acid produced in these reactions.

The nickel and cobalt sulphates are converted to their respective ammines, upon the addition of ammonia, in order to facilitate the **reduction of nickel** with hydrogen (unit operation 4):

$$NiSO_4 + nNH_3 \rightarrow Ni(NH_3)_nSO_4 \quad (26)$$

Ammonium sulphate crystals, recycled from the **mixed double salt** process (unit operation 5), are added to the nickel solution, to serve as a buffer and to improve the morphology of the nickel powder produced. Nickel hydroxide can also form upon ammonia addition, should insufficient ammonium sulphate be present.

The Sherritt hydrogen reduction process is used to produce nickel powder and ammonium sulphate. The reduction involves three reactions (Boldt, 1967). The nickel is reduced to the metal, producing hydrogen ions which react with ammonia to form ammonium ions. Ammonia reacts with unreduced nickel ions to form nickel ammine complexes.

$$Ni^{2+} + H_2 \rightarrow Ni + 2H^+ \quad (27)$$

$$H^+ + NH_3 \rightarrow NH_4^+ \quad (28)$$

$$[Ni(NH_3)_{n-1}]^{2+} + NH_3 \rightarrow [Ni(NH_3)_n]^{2+} \quad (29)$$

(where n=1 to 6)

Increasing the free ammonia concentration reduces the hydrogen ion concentration (reaction 28), which promotes the reduction of nickel (reaction 27), according to Le

Chatelier's Principle. However, such an increase in free ammonia would also promote the formation of nickel ammine complexes (reaction 29), which renders the nickel unavailable for reduction. In practice, it has been found that the optimum ratio is two moles of free ammonia per mole of nickel ions (Boldt, 1967).

A ferrous sulphate slurry is used to provide nuclei for the nickel to grow on, thereby reducing the amount of nickel plating out on the process equipment. The ferrous sulphate also serves to catalyze the nickel reduction reaction. The slurry is pumped into the autoclave under a blanket of nitrogen, which prevents oxidation to the ferric ion. Particle growth and agglomeration must be controlled, in order to obtain a powder of suitable physical properties. The nickel precipitates out of the solution onto the nucleating particles, which are allowed to settle once the reduction is complete. The end solution is withdrawn and a new batch is charged, and the operation repeated.

The nickel particles in the autoclave thus increase in size and bulk density with successive batch reductions, which are termed "densifications". The nickel powder particles also catalyse the reaction, thus once started the process is autocatalytic (Boldt, 1967). When the reduction cycle is complete, the entire charge is withdrawn. Nitric acid is then used to leach plated nickel metal from the internals of the autoclave, and the nickel nitrate thus produced routed to the copper cementation circuit. The nickel powder is essentially spherical, with nodular irregularities on the surface, such that "each particle resembles a small metallic raspberry" (Burkin, 1987). The powder is washed, dried and briquetted, with the aid of an organic binding agent. Some of the briquettes are then sintered at 900°C, using steam to remove carbon, and hydrogen to remove sulphur. Carbon dioxide and hydrogen sulphide are thus produced, and are vented to the atmosphere.

2.4.3) Cobalt solution purification and reduction

The soluble sulphates (Co, Ni, Cu, Fe and Mn as well as As) present in the nickel reduction end solution are cooled under acidic conditions, which result in the precipitation of various **base metal double salts** (unit operation 5), as follows (Plasket and Dunn, 1986b):

$$MeSO_4(aq) + (NH_4)_2SO_4 + 6H_2O \rightarrow [MeSO_4.6H_2O](NH_4)_2SO_4 \qquad (30)$$

The filtrate is neutralised with ammonia, and then returned to the nickel molar ratio adjustment circuit and the **ammonium sulphate** plant (unit operation 7).

The mixed double salts are dissolved by addition of ammonia, which reverses reaction (30). The iron is oxidised to the ferric state upon aeration, and subsequently precipitated together with the arsenic (unit operation 6), according to reaction (24), and via goethite (FeO.OH) formation.

Oxygen is then used to oxidise cobalt to cobaltic pentammine (the nickel is not oxidised under these conditions) (Plasket and Dunn, 1986b):

$$4CoSO_4 + 2(NH_4)_2SO_4 + 16NH_3 + O_2 + 2H_2O \rightarrow 2[Co(NH_3)_5H_2O]_2(SO_4)_3 \quad (31)$$

The solution is acidified with sulphuric acid and cooled to below 30°C, which results in nickel-ammonium double salt precipitation. The cobaltic pentammine complex remains stable in the acidic environment, thus the cobalt remains in solution (Mackiw and Veltman, 1982). In this manner, nickel is separated from the cobalt. The nickel double salt is redissolved in ammonia, and returned to the nickel circuit.

Some of the manganese present is also oxidised during this oxidative ammination step:

$$2MnSO_4(aq) + 4NH_3 + O_2 + 2H_2O \rightarrow 2MnO_2 + 2(NH_4)_2SO_4 \quad (32)$$

The remaining manganese is removed upon boiling the cobaltic solution (Plasket and Dunn, 1986b):

$$MnSO_4 + [Co(NH_3)_5H_2O]_2(SO_4)_3 \rightarrow 2CoSO_4 + MnO_2 + 2(NH_4)_2SO_4 + 6NH_3 \quad (33)$$

Recycled cobalt powder is then added to reduce the cobaltic solution to the cobaltous state. The ammonia that is released results in the formation of cobaltous ammine complexes of the form $Co(NH_3)_nSO_4$, where n>2 (Plasket and Dunn, 1986b).

$$[Co(NH_3)_5H_2O]_2(SO_4)_3 + Co \rightarrow 3Co(NH_3)_2SO_4 + 4NH_3 + 2H_2O \quad (34)$$

Copper is also cemented by the cobalt powder. This small amount of copper is recycled to the jarosite precipitation operation.

$$CuSO_4(aq) + Co \rightarrow Cu + CoSO_4(aq) \quad (35)$$

The cobalt solution is finally reduced with hydrogen, to form cobalt powder (Plasket and Dunn, 1986b):

$$Co(NH_3)_nSO_4(aq) + H_2 \rightarrow Co + (NH_4)_2SO_4 + (n\text{-}2)NH_3 \quad (36)$$

where n=3-6.

The nucleation reduction is initiated by a NaS-NaCN catalyst (Burkin, 1987). Approximately thirty densifications are performed per cycle, that is, prior to discharge of the entire tank. Cobaltic cobalt solution is used to dissolve plated cobalt from the autoclave interior, after about three densification cycles. The cobalt is washed and dried under nitrogen, and the reduction end solution is returned to the mixed double salts circuit.

2.4.4) Copper solution purification and electrowinning

The second stage leach solution is treated with sulphurous acid (unit operation 12), in order to remove selenium and tellurium, which would contaminate the copper product. (Refer to reaction (18)). The solids thus produced are sent out for toll refining.

The copper is then **electrowon** (unit operation 13) using stainless steel cathodes and lead anodes, as given in the two half-cell reactions:

$$2Cu^{2+} + 4e^- \rightarrow 2Cu^0 \quad (37)$$

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^- \quad (38)$$

A layer of polypropylene balls is used to break up the oxygen gas bubbles generated, and reduce acid mist formation. The sulphuric acid generated during this electrowinning process, is recycled to the primary leach circuit.

In this manner, the BMR extracts metals from the matte prior to precious metal refining, which would otherwise make such refining difficult and uneconomical. Whilst providing the precious metal concentrate, the BMR also generates income from the sales of the nickel, copper and cobalt produced.

Chapter 3: GOAL DEFINITION AND SCOPING

3.1) INTRODUCTION

The goal definition section of a LCA should provide a definition of the system studied and its boundaries. This is an important step in a life cycle assessment, as it determines which inputs and outputs are to be included, and which are to be considered as part of the general environment (SETAC, 1993). For a process-based LCA, this would involve the determination of which consumptions and emissions are to be considered as arising from the process being assessed (Crittenden, 1994). It must be noted that clarity and transparency in this stage of the LCA is critical in order to ensure the credibility of the results.

The intended use of the assessment and the limitations for its use for other purposes must be stated. In conjunction with this, the data quality must be defined. The geographical and temporal limitations of the result, and any organisation's participation (financial and otherwise) in the study should also be included (Weidema, 1993). The function of the system and the functional unit associated with it must be defined in such a way that ambiguity is reduced and comparisons can be made between different studies.

3.2) THE PURPOSE OF THE LCA

3.2.1) The application and intended use of results

The major envisaged application of this cradle to gate life cycle assessment is as an environmental support tool for Impala's decision making, with respect to technology choice and process optimisation and improvement in the Base Metal Refinery. In addition, areas of the BMR operations which contribute most significantly to potential environmental impacts are to be highlighted, so that potential improvement opportunities in environmental performance may be identified.

Besides these goals, which were the thrust of this study, other applications were found to exist in practice. For example, information gathered during this LCA (with specific reference to the data inventory), will contribute to the establishment of quantitative targets for the determination of continual improvement in environmental

performance and the prevention of pollution, as required by ISO 14001, as well as the Responsible Care initiative to which Impala subscribes.

3.2.2) The target group

As the environmental model developed will be used to evaluate the environmental merits and drawbacks of alternative process options, it is envisaged that process and project engineers of the Base Metal Refinery of Impala Platinum Limited will form the major portion of the target group, in conjunction with employees of the Environmental Section of the Safety, Health, Environmental, and Quality (SHEQ) Department of Impala Refineries. The information thus generated will, however, be conveyed to higher management, who therefore form the secondary target group.

In addition, others may be interested in the results of this study, such as researchers in the field of life cycle assessments (specifically those in the nickel industry, for example, the Nickel Development Institute). Care must be taken, however, that the results are used in context with respect to the scope of the study and the assumptions made.

Due to the fact that the primary target group is not expected to be familiar with the principles of LCA, brief overviews explaining the purpose of each step are included. It should also be noted that if the results of the LCA were to be used for a regulatory requirement, a higher degree of reliability would be required than for use within the company (Heijungs, 1992a).

3.3) THE SCOPE OF THE LCA

3.3.1) System boundaries

i) Spatial boundaries:

It has been noted that "an assessment of an entire system, a network of industrial operations over its product life cycle, is difficult" (Vigon, 1998c). In this study, the major difficulties lay in a lack of relevant public databases (with respect to reagents, for example) and the fact that the life cycle forms a vastly spatially diverse system (for example products and by-products are sold overseas). Various simplifications and assumptions therefore had to be made, in order to make the study feasible, in terms of time and cost involved. These are to be explained and discussed.

The ideal, theoretical cradle-to-grave boundary of a life cycle assessment for the processing of sulphidic, precious metal bearing ores (such as that from the Merensky Reef) is given in Figure 3.1. Resources from the environment are inputs to the process system, and wastes and emissions which are generated by the processes are released to the environment. All of the processes from initial mining of the ore, through refining and value-adding operations, to use and final disposal of these products are included, as are transport steps.

A distinction can be made between the foreground system (the BMR processes), and the background system (the balance of that contained within the LCA boundary). The impacts associated with the foreground system are direct impacts, while those related to the background system are termed indirect impacts (for example, the impacts associated with electricity generation) (Stewart and Petrie, 1996c).

The system boundaries used in this study were those of the foreground system, as illustrated in Figure 3.1, with the impacts relating to the manufacture of reagents and the generation of electricity used by the BMR also being included. The overall system boundary is thus shown in Figure 3.2. The Life Cycle Assessment performed may be described as being "first-order", because the mining and pre-concentration of the ore were not included in the assessment, although it is acknowledged that these primary beneficiation processes will affect the BMR operations (refer to section 3.4).

By focusing on the impacts associated with the BMR operations, these impacts were not diluted by impacts generated during mining and primary concentration processes, or by those impacts incurred downstream of the BMR operations (for example, once the BMR products enter the manufacturing realm). In this manner, changes in BMR processes can be meaningfully assessed with respect to environmental performance, as processes common to all alternatives may be omitted from the system boundary (von Blottnitz, 1994). Areas of the BMR operation of greatest potential improvement in environmental performance may also be identified.

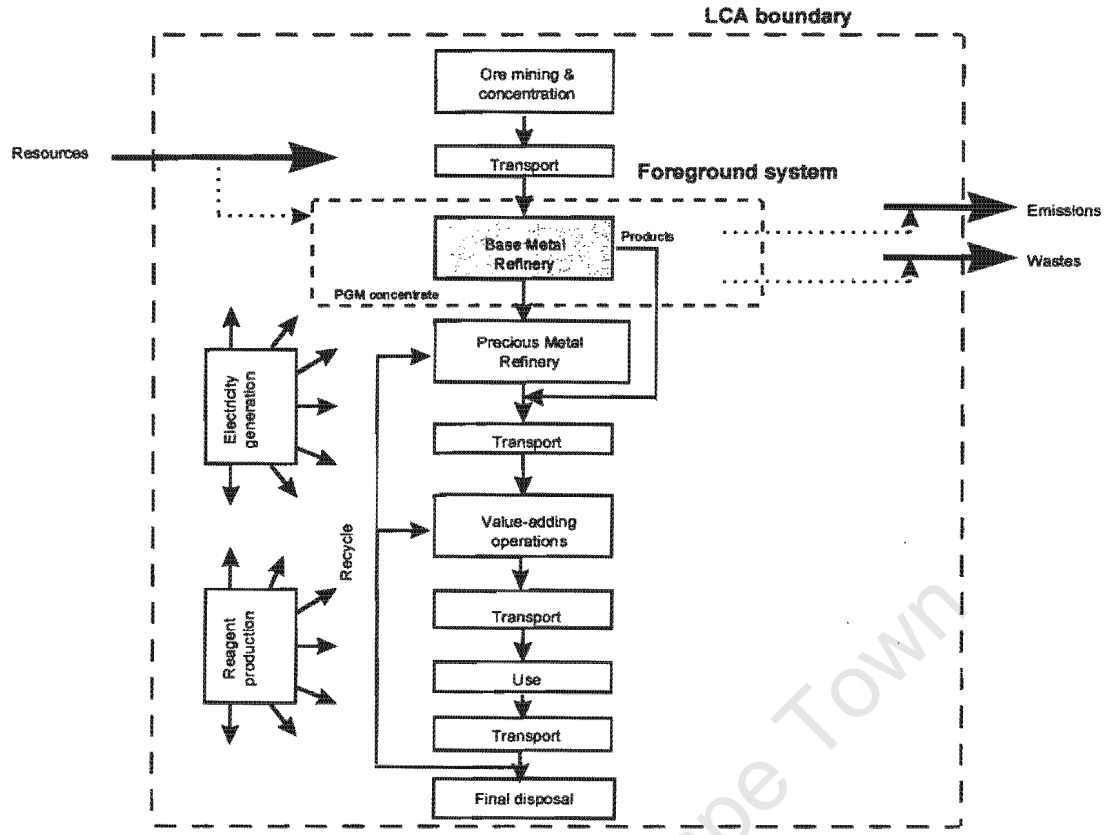


Figure 3.1: Theoretical LCA boundary for the processing of sulphidic PGM-bearing ores.

The geographical boundary thus encompassed the BMR, situated in Springs, Gauteng, South Africa, as well as the locations of electricity generation and reagent manufacture. The mining and initial beneficiation operations in Rustenburg, South Africa, as well as the locations of all customers of products and by-products were excluded.

Figure 3.2 illustrates the subject of this project in more detail. The overall BMR operations were divided into three subsections: the BMR process itself, steam generation, and hydrogen production. These divisions were made in order to improve transparency in the mass balances, and to clarify the audit trail of environmental impacts back to their sources in the process.

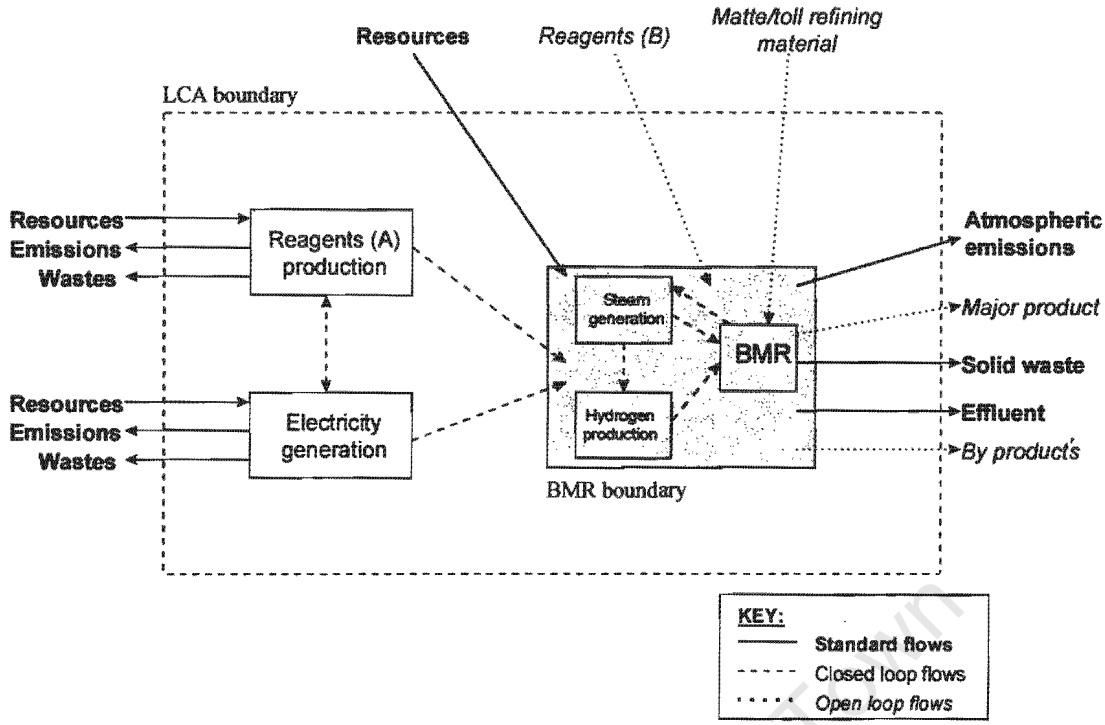


Figure 3.2: First level actual LCA boundary.

Three types of flows are distinguished in Figure 3.2. Firstly, standard flows are those which interact directly with the environment, and thus have direct impacts. Examples would include water and air as inputs and emissions to the atmosphere as outputs. Closed loop flows are "internal" flows within the system considered (which have no environmental impacts directly associated with them), such as steam flowing from the steam generation sub-section to the BMR process sub-section. The environmental impacts of open loop flows were excluded from the assessment. For example, as this study was to the "gate", impacts arising from value-adding operations downstream were excluded, and the products were thus open loop outputs. It can be seen in Figure 3.2 that some of the environmental impacts associated with reagent production were included (Reagents (A), related back to standard flows), whilst others were not (Reagents (B), open loop flows). This is explained in section 3.3.2.

Figures 3.3a and 3.3b provide more detail regarding the inputs and outputs to the BMR process subsection. This is further expanded to include the individual unit operations of the BMR in Figure 3.4 for the purposes of mass balancing and traceability of impacts. The development of this flowsheet is explained in section 4.2. The hydrogen and steam generation plants, which provide reagents and energy

to the BMR, are similarly detailed in Figures 3.5a and 3.5b, and Figures 3.6a and 3.6b, respectively.

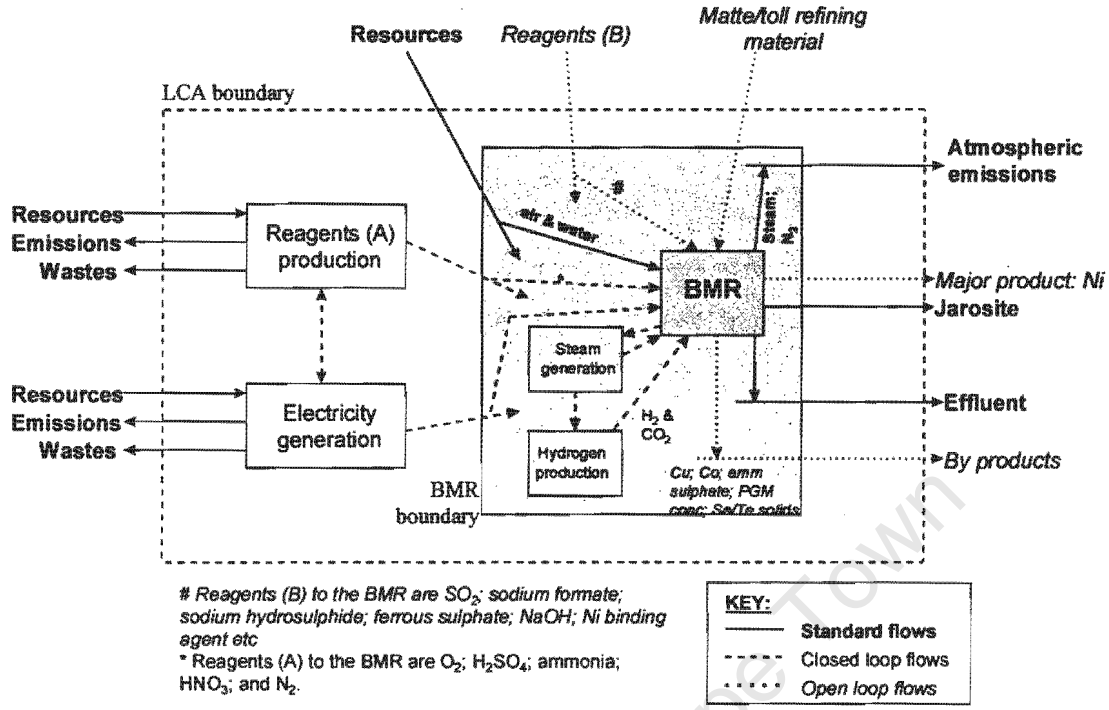


Figure 3.3a: Second level system boundary: Base Metal Refinery detail.

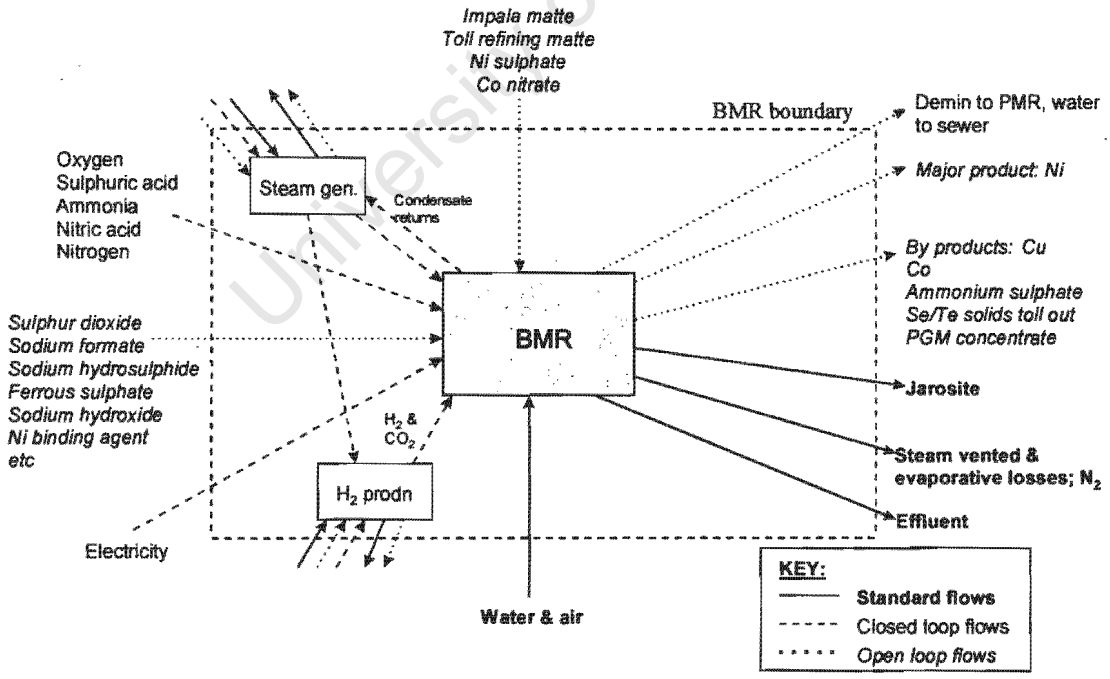


Figure 3.3b: Second level sub-system boundary: Base Metal Refinery.

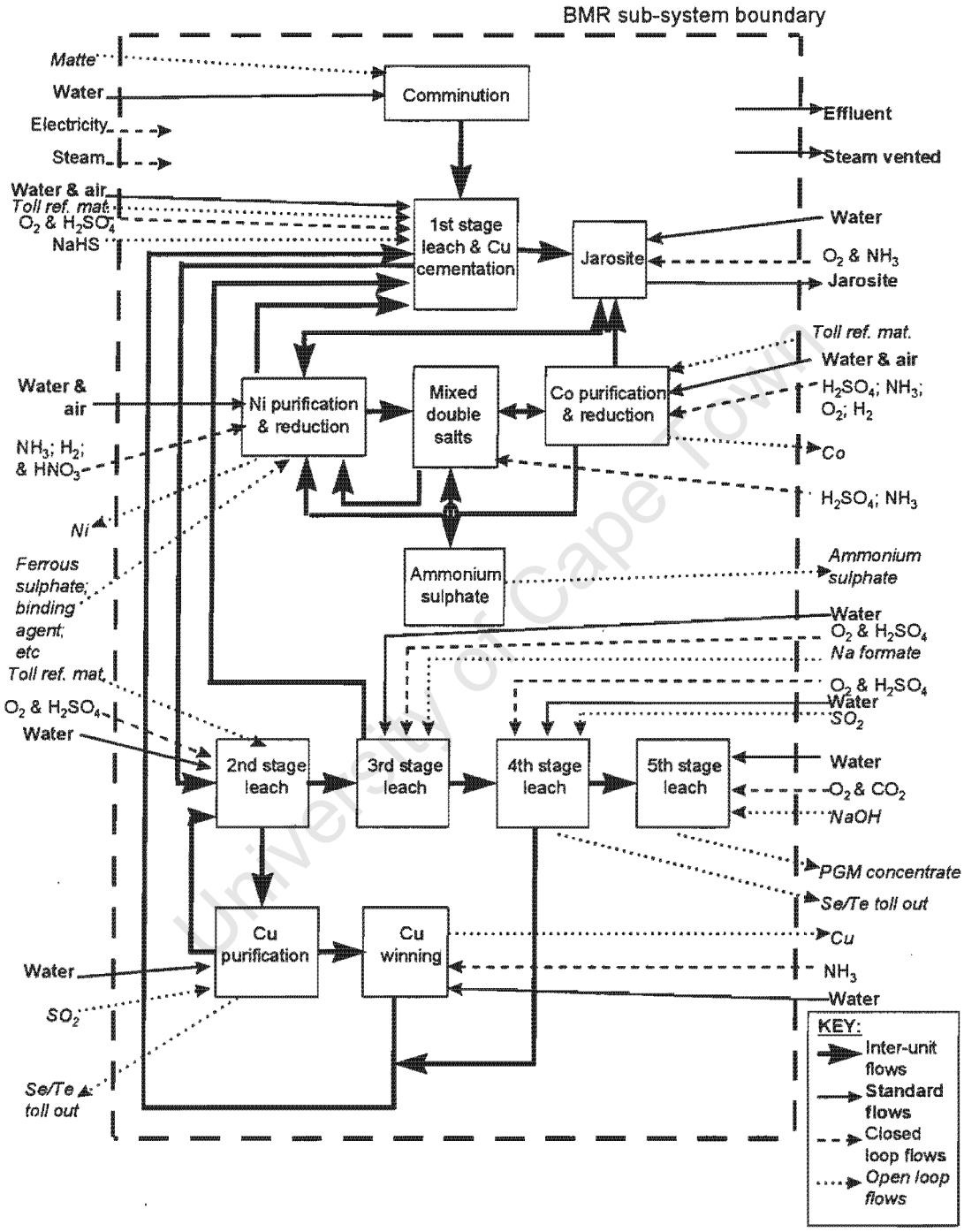


Figure 3.4: Third level sub-system boundary: Base Metal Refinery.

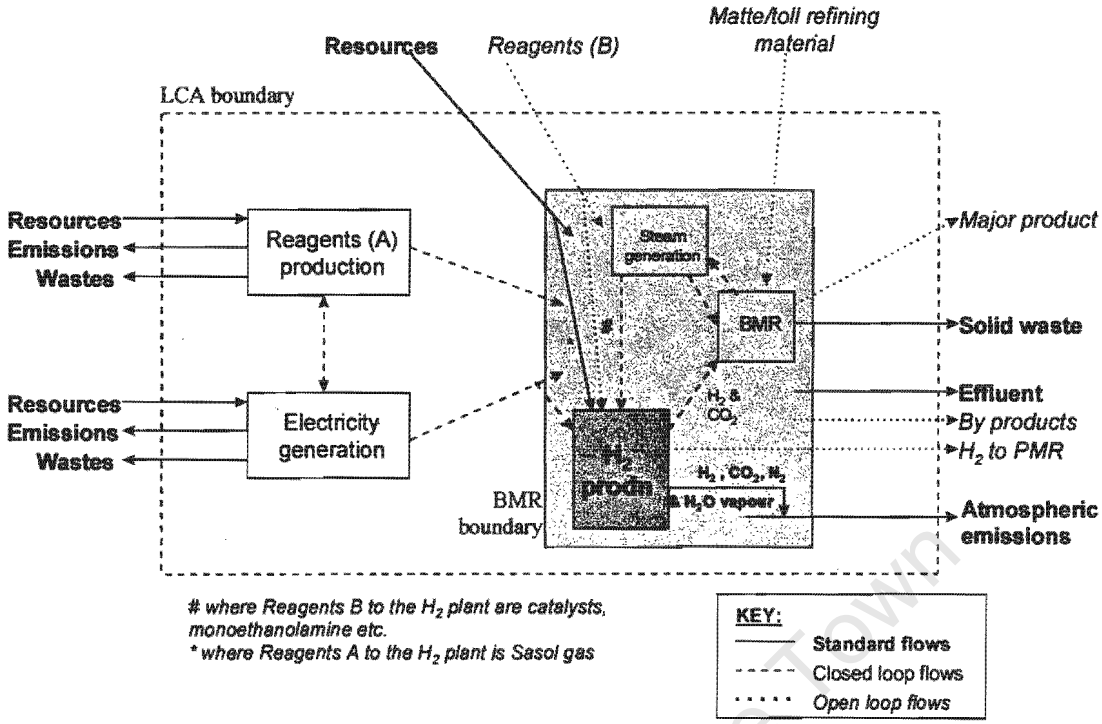


Figure 3.5a: Second level system boundary: Hydrogen plant detail.

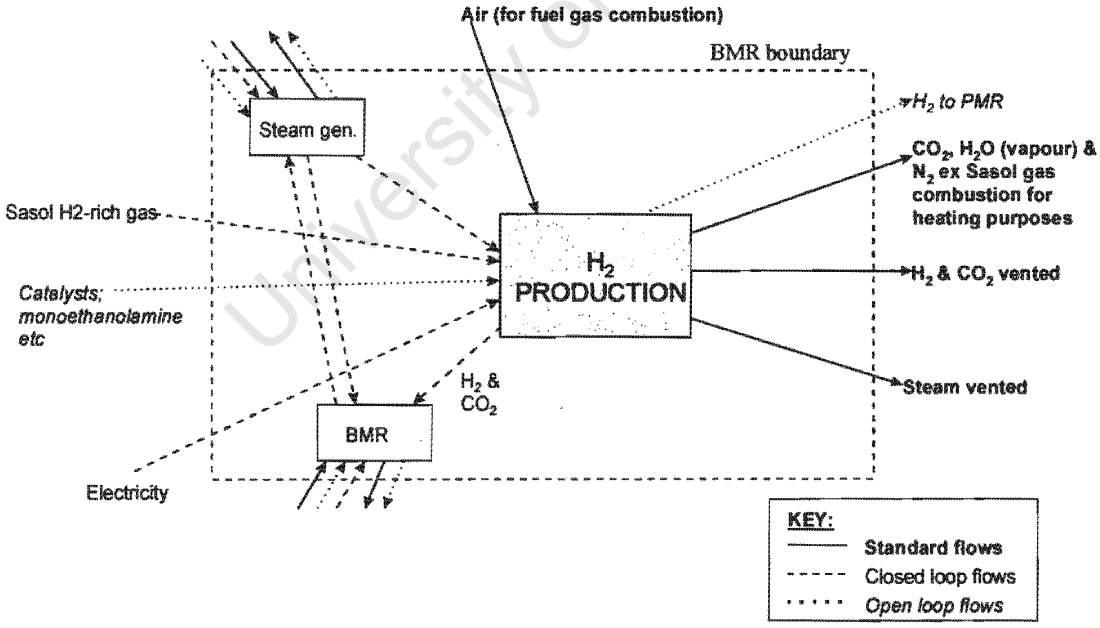


Figure 3.5b: Second level sub-system boundary: Hydrogen production.

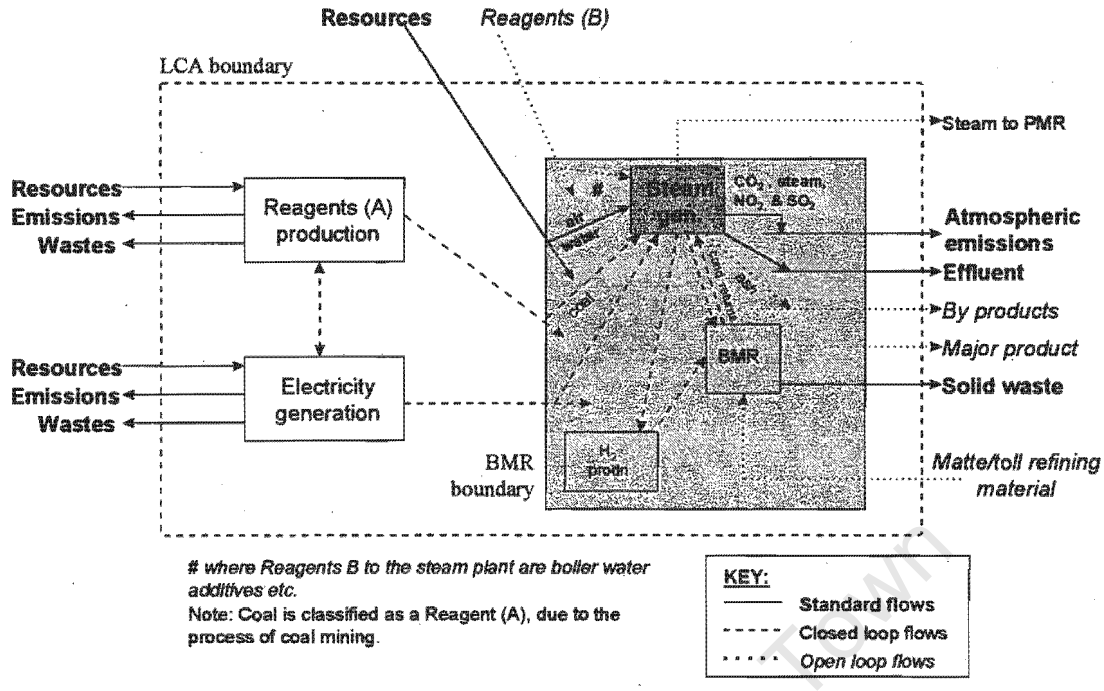


Figure 3.6a: Second level system boundary: Steam generation plant detail.

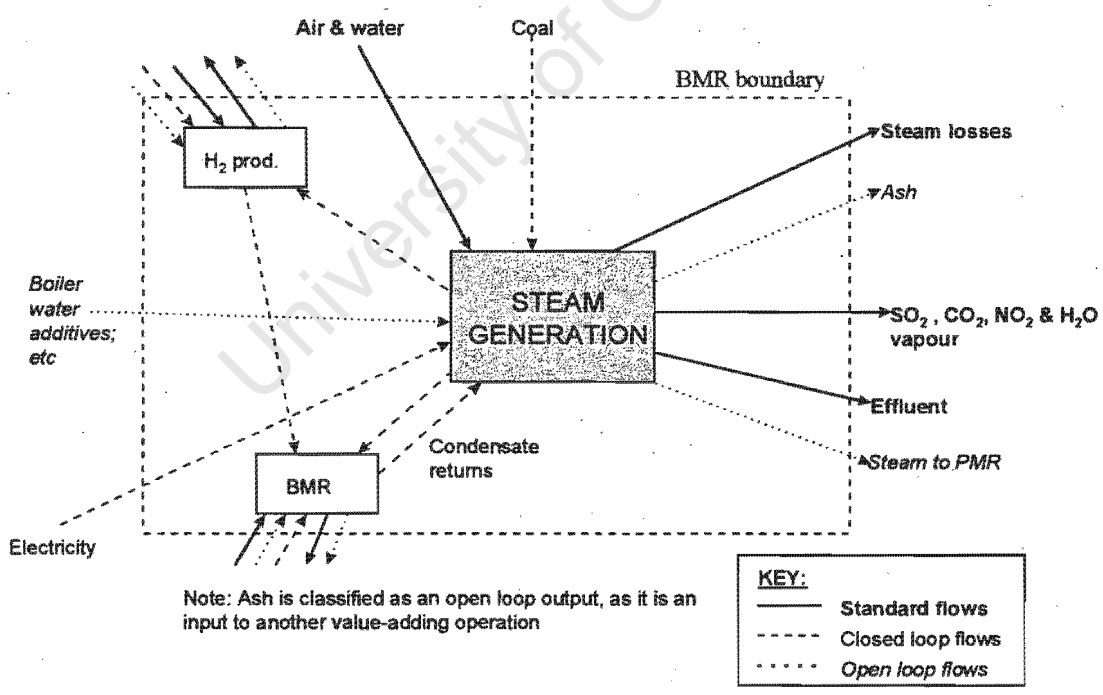


Figure 3.6b: Second level sub-system boundary: Steam generation.

ii) Temporal boundaries:

The monthly data studied covered the period from January 1995 to July 1997, inclusive. This starting date for data collection was chosen because it is the date at which a metal accounting system was implemented, which enhanced data documentation and subsequent availability. In addition, various toll refining contracts were initiated around that time, which provided a range of raw materials for processing, besides the matte which is produced from the ore mined by Impala. This had an effect on materials usage and production rates. Data was therefore collected from this point up until the time at which this project was started. Data subsequently generated may be included in the environmental data inventory upon completion of the project.

Months of low production, primarily due to problems with matte deliveries (i.e. the supply of raw material), were included in order to ascertain the consequent changes in the environmental impacts. The effects of short down-times due to maintenance and the like, will have been absorbed into the monthly average data used. Environmental profiles were generated for each month, as well as for an overall average.

3.3.2) The level of detail of the LCA

This study is the first of its kind at Impala Platinum and certainly one of the first in the nickel refining industry (McKean, 1998), thus the scope of the assessment was somewhat limited by a lack of available data as well as by time constraints.

Thus only those reagents for which public life cycle inventories could be obtained were included in the system boundaries. Rough inventories based on assumptions and theoretical values were avoided in order to keep uncertainties to a minimum. Reagents which are used in small quantities (≤0.03t/t Ni produced) were not included in the impact calculations, but are mentioned in a note to the inventory, for completeness and to ensure that environmental impacts associated with these chemicals are not overlooked. Examples of such materials include additives to the cooling water and boiler systems, and the numerous reagents used in the laboratories on site. The total percentage of reagents (excluding air, the H_2 catalysts and carbon used) thus omitted was less than 0.2% by mass of all inputs. Sensitivity analyses were conducted to validate the omission of a number of these reagents (refer to Chapter 6).

The transport of bulk reagents to the BMR premises was excluded from the assessment. Again this was validated by a sensitivity analysis. The environmental impacts of the product and by-products were only considered to the gate, thus transport of these materials to customers was excluded.

The production and maintenance (including lubricating oil usage) of capital equipment employed in the BMR were excluded from the assessment. Major maintenance is usually performed by outside contractors, who assume responsibility of disposing of any wastes generated which are not re-processed by Impala. Similarly, the stationery used for administration purposes in the BMR was not included. These exclusions are consistent with LCA practice, but they obviously introduce a degree of uncertainty in the results.

Lighting of the plant was included, in that the total electricity of the BMR operations was employed in the impact assessment. Packaging of the product and by-products was excluded, as it is minimal, with most of the materials being loaded directly onto rail coaches or road trucks for transportation to the customer.

The PEMS (Pira's Environmental Management System) software package and related database (version 4, 1998) were used for the impact assessment and improvement analysis. The following system boundaries were drawn in deriving these material and energy databases (Pira, 1998):

- Materials and transportation data was sourced from the ETH (Eidgenössische Technische Hochschule: Swiss Federal Institute of Technology, Zürich) data set (1994). The life cycle inventory profiles include the main production sequence, from extraction of raw materials up to and including the manufacture of the material. The production and use of fuels and secondary energy generation (heat and electricity) are also included. Manufacture and maintenance of capital equipment and the manufacturing establishments is included, with respect to the energy generation stages. Post-manufacture stages (such as transport and final disposal) are excluded, but waste management of process wastes is included.

- The energy generation data (production of fuels and electricity generation) was sourced from the Energy Technology Support Unit, Harwell. (Report entitled

"Environmental Benefits of Offset Energy" - 1996). The data has similar system boundaries to the ETH data discussed above, upon which it is based. It also includes electricity distribution losses.

3.3.3) Data requirements

The information required for the assessment was assembled by the author from Impala's metal accounting and process records, where available. Other data was obtained from interviews with process personnel, and by analysis of samples taken by the author. The data collected was not restricted by limiting the environmental effects considered, because a full inventory was required to provide an overview of the environmental impacts associated with the BMR operations.

It was important that real data was used, as opposed to target or theoretical values, as the BMR operations are dynamic, and significant fluctuations and variations may occur. A model of the BMR process, developed in Metsim (a metallurgical process simulation software package used to perform material and energy balances), was used to estimate flowrates. These were confirmed by BMR process personnel.

For electricity generation, a LCI based on South African coal-based generation practice was used (Notten, 1998), as it is obviously more applicable than the European and UK electricity LCIs given in the PEMS database (these include nuclear and hydro-generation methods, which are not used for electricity generation in Gauteng, South Africa).

The problem-oriented approach was used to classify the environmental burdens. All of the impact categories available in the PEMS software were considered, in order to obtain an understanding of the relative magnitudes of contributions to each category, as well as their month-to-month fluctuations. The problems considered were thus global warming potential, resource depletion, acidification, ecotoxicity (both aquatic and terrestrial), human toxicity, eutrophication, smog (based on both an ethene reference substance and NO_x), and ozone depletion. Water usage by the BMR processes (in kg/kg Ni produced) was also included as an impact category, as discussed in section 5.3.3.

A number of the impact categories (acidification, eutrophication, global warming, resource depletion and smog), for which annual world effect scores were available

in the PEMS version 4 software, were normalised. This facilitated comparisons between impact categories. Although the greenhouse effect is typically a global issue, acidification is more of a regional issue, while eutrophication and smog may be viewed as local problems, and resource depletion spans these reference scales. The categories which have regional and local effects should ideally be compared to a regional or local reference scale. Unfortunately, due to the current lack of information in this regard (or lack of transparency in the collection methods of the data available), the global values had to be used. For the water usage impact category, water usage by Impala's BMR was compared to the industrial water consumption in the Springs area (refer to 5.4.2), as water availability and usage patterns vary from region to region in South Africa.

3.4) ASSUMPTIONS AND LIMITATIONS OF THE STUDY

The purpose of this study was to provide a LCA for the activity of base metal refining, and not specifically for the refining of nickel from matte produced by Impala's Mineral Processes. The BMR could exist without Impala matte, as there are other sources of raw materials (such as toll refining of base metal-containing materials), although the LCI would then change somewhat due to altered reagent requirements. The impacts associated with the mining and initial beneficiation of the Impala ore were therefore excluded from this study.

It must be borne in mind that the purpose of this model is not to evaluate environmental impacts associated with specific upstream operations. Assessment and scope for improvement is thus rather focused on the base metal refinery itself, which is viewed as a separate processing unit. The impacts associated with matte production and their respective magnitudes are assumed to be fixed and unable to be altered (the mining and MinPro operations do not depend significantly on those of the BMR).

Similarly, the impacts associated with the production of toll refining materials have not been included, due to a lack of readily available data and the fact that the BMR is not dependent on a specific raw material supplier for operation.

It is assumed that the reagents which were excluded (those used in relatively small amounts) do not make a significant contribution to the environmental impacts

associated with the BMR operations. A qualitative discussion of the potential environmental impacts of these excluded reagents is included for completeness, however.

As noted previously, the impacts were only considered to the gate of the BMR operations, thus the transport of BMR products, the impacts of subsequent value-adding operations involving these materials to produce other products, and the use and final disposal of these were not targets of the study.

Where the PEMS version 4 database was used for input data (such as reagents used in the BMR process), it was assumed that the inventories were applicable to this project, that is, the production processes, efficiencies and so on, are identical to those of the actual suppliers to the BMR. This implies identical impacts. Assumptions with respect to mass balance calculations and so on are elaborated on in Chapter 4.

As has been previously discussed in some detail, different processing options for base metal refining are currently used commercially. Caution should therefore be exercised when drawing conclusions regarding the BMR industry as a whole, as the results are site and process specific.

3.5) MATCHING SCOPE WITH PURPOSE

The purpose of this study was to develop an environmental model which highlights areas of the BMR operations which contribute most significantly to potential environmental impacts. In this way, areas of potential improvement in environmental performance may be identified. The scope covers all significant aspects of the BMR operations, which could practically be reformulated to reduce potential environmental impacts. In this manner, the scope matches the purpose of the study. Similarly, the environmental impacts associated with various BMR process options may be evaluated. The conclusions reached are, however, subject to the assumptions and limitations of the study.

3.6) THE FUNCTIONAL UNIT FOR THE LCA

The primary products of Impala Platinum's Base Metal Refinery are nickel, copper and cobalt, with ammonium sulphate produced as a by-product. Precious metal concentrate is supplied to Impala's PMR for refining, and Se/Te residues are sent to toll refiners for further processing to saleable products. The functional unit was chosen as one ton of nickel produced, by virtue of the quantity of nickel production and the revenue it generates, as compared to the other products. This functional unit will also facilitate benchmarking of environmental performance with other base metal refiners. The choice of this functional unit will be reviewed later, when a scenario is studied which changes the ratio of the products produced (Chapter 8).

By using nickel production as the functional unit for this study, 100% of the potential environmental impacts of the BMR are allocated to the nickel produced. Before benchmarking against figures of other nickel producers, it might become necessary to allocate percentages of the impacts to byproducts (such as the PGM concentrate). Otherwise the environmental profile relating to Impala's nickel production might be portrayed as being unrealistically high.

3.7) DATA QUALITY IN THE LCA

Average monthly analytical values (obtained from process control and metal accounting records) were used in the mass balances, as is consistent with LCA methodology (refer to section 4.1). This may have prevented peaks or fluctuations in daily results from being noted. The largest errors would thus have occurred in mass flows which fluctuated to a significant extent in daily composition and quantity, such as effluent leaving the site.

The level of accuracy of the used data varied. The analyses performed for metal accounting purposes were more accurate than those performed by satellite laboratories for process control, for example (although the accuracy also depends on the sample matrix and the concentration of the analyte).

The accuracy of reagent usage and solids generation were dependent on volume, flowrate and mass measurements. Average flowrates (as verified by BMR

personnel) were used in the elemental mass balances. The overall error was therefore estimated to be between 10 and 15% (refer to section 4.3), although the absolute error in the month-by-month LCIs was larger than this in some cases, due to short-term faults with metering equipment and so on (refer to Appendix 1). This was confirmed by the mass balance closures. Cross-checking of data between sources was performed wherever possible. The average data used and the mass balances generated were checked and verified by a team of Senior Process Engineers from Impala's BMR.

Chapter 4: DATA COLLECTION AND PREPARATION OF THE LIFE CYCLE INVENTORY

4.1) INTRODUCTION

The overview of Life Cycle Assessment methodology (Section 1.2), included a discussion on the life cycle inventory step, however a few points deserve further mention. The preparation of the life cycle inventory forms perhaps the most crucial step of any life cycle assessment, as the validity of the results the LCA generates is a function of the accuracy of the data employed. It is necessary, however, to obtain a balance between the accuracy and completeness of the data and the cost and time involved in obtaining such information. This is necessary because these practical constraints would undeniably affect the applicability of life cycle methodology as an environmental tool in the base metal refining industry (or in any industry for that matter).

Industrial operations have been likened to biological systems, in order to encompass use of materials and generation of wastes: "Industrial metabolism, by analogy, is the set of physico-chemical transformations that convert raw materials (biomass, fuels, minerals, metals) into manufactured products and structures (i.e.: "goods") and "wastes" (Ayres and Simonis, 1994). It is information relating to these inputs and outputs which is gathered to form a LCI, with inventory tables compiled per process or per functional unit (Guinée, 1993b).

In terms of inputs, energy consumption is often a vital factor, due to the consumption of non-renewable resources, as well as the emissions associated with thermal power stations (von Blottnitz, 1994). Transport may also be a significant source of environmental impacts, especially when materials of low density and low value are transported, such as domestic waste (Clift, 1993a).

Average data is generally used in a LCA: "As a life cycle assessment is based on a functional unit with an arbitrary magnitude for a given period, the aim is not to consider short-term variations in a process but rather the overall changes in magnitude which may occur during a given period. It is best to use long-term marginal process data. In many cases these can be approximated by using the average process data during normal operations" (Heijungs, 1992a). The source of

data used in the study must be clearly identified, and its representativeness and quality must be stated (Denison, 1993). Any gaps in the data should also be noted.

It has been commented that LCA will remain a selectively used tool until public databases are available and accepted streamlined methods for screening applications are developed (Vigon, 1997d). Further, widespread use of LCA has been hampered by the perceived need for the repetitive collection of a massive amount of data, as time and effort is often wasted in the duplication of work already completed by others on input and auxiliary (background) processes, although inventory data is also presently lacking for wide sectors of industry (Vigon, 1998b). A balance needs to be reached "between the desire to have all of the data and the need to make informed decisions, even if the knowledge upon which these decisions are made is incomplete and uncertain" (Vigon, 1997d). Thus a streamlined approach may be useful to identify possible system issues and trade-offs, followed by the use of an absolute analysis to reveal the details.

LCA methodology to quantify uncertainty in the inventory data set is still in its infancy (Vigon, 1997a), which is a concern as confidence in life-cycle inventories is dependent upon an understanding of the source and extent of uncertainties in the data and the results thus produced (Finnveden and Lindfors, 1998). Indeed, careful consideration of data quality can improve the interpretation of LCIs and thereby increase their utility.

As this case study involved the development of a "cradle to gate" environmental model for Impala Platinum Ltd's Base Metal Refinery, the LCI was primarily based on data which was on hand, in order to reduce the cost and time involved in the preparation of the inventory. Transparency was achieved by the provision of details which allowed results to be traced back to the source of data, and any assumptions upon which calculations were based were explicitly stated.

In this chapter, the process flowsheet will be defined, and the sources and the estimated relative accuracy of the data employed will be given. Mass balances for the BMR will be presented, both in terms of overall inputs and outputs and on an elemental basis. Impala Platinum Refineries' water management system with regards to the BMR will also be discussed.

4.2) PROCESS FLOWSHEET

The first step in preparing the LCI involved the development of a suitable flowsheet to describe the unit operations of Impala's BMR. The strategy employed in the development of this flowsheet was driven in part by the process flow and analytical data availability (governed by the current division of the plant into domains), and in part by the following considerations used in defining unit operations for the purpose of LCA (Stewart and Petrie, 1996d).

If the function of two units was the same, they were incorporated into one unit. The reduction and subsequent handling of nickel, for example, serves to produce nickel in a saleable form, and thus these operations were grouped together. Units which generated large quantities of waste, or which had high through-puts or high reagent additions were kept separate for traceability purposes, such as the jarosite process which generates a hazardous waste. Similarly, units with high energy consumptions (such as comminution (milling) and copper electrowinning) were identified.

The BMR is divided into two plants: plant A and plant B, which operate in parallel. Thus there are two comminution, 1st stage, and Cu cementation circuits. The Ni streams generated by the two plants are then combined at the jarosite circuit. Similarly, there are two 2nd stage leach circuits, with the Cu solutions joining at Cu purification, while the PGM containing solids are combined at 3rd stage leach. Due to analytical protocols and the similarity of the processes (and thus the environmental impacts associated with them), the two plants were combined for the purposes of this study. They could, however, be similarly defined as separate entities, should this be deemed desirable at a later stage.

Thus, in summary, the flow diagram was developed in a manner which facilitated traceability of processes which were perceived to have potentially significant environmental impacts. Consequently, thirteen unit operations were defined as follows:

UNIT NUMBER	UNIT OPERATION
1	Comminution
2	1st stage leach & Cu cementation
3	Jarosite
4	Ni purification & reduction
5	Mixed double salts
6	Co purification & reduction
7	Ammonium sulphate
8	2nd stage leach
9	3rd stage leach
10	4th stage leach
11	5th stage leach
12	Cu purification
13	Cu winning

Table 4.1: Definition of unit operations.

(Note: Unit operation 4 includes nickel handling operations)

The flowsheet thus derived, as depicted in Figure 4.1, is detailed only to the point of main process flows. The process information and chemistry relating to each unit operation was detailed in section 2.4. Residue (solid) flows are differentiated from solution flows by bold arrows. The main components of each stream are indicated, with major components given in bold. Products and by-products are also shown in bold. Recycle streams which do not cross unit operation boundaries were excluded from both the flowsheet and the life cycle inventory, as is consistent with LCA practice, as they do not interact with the environment.

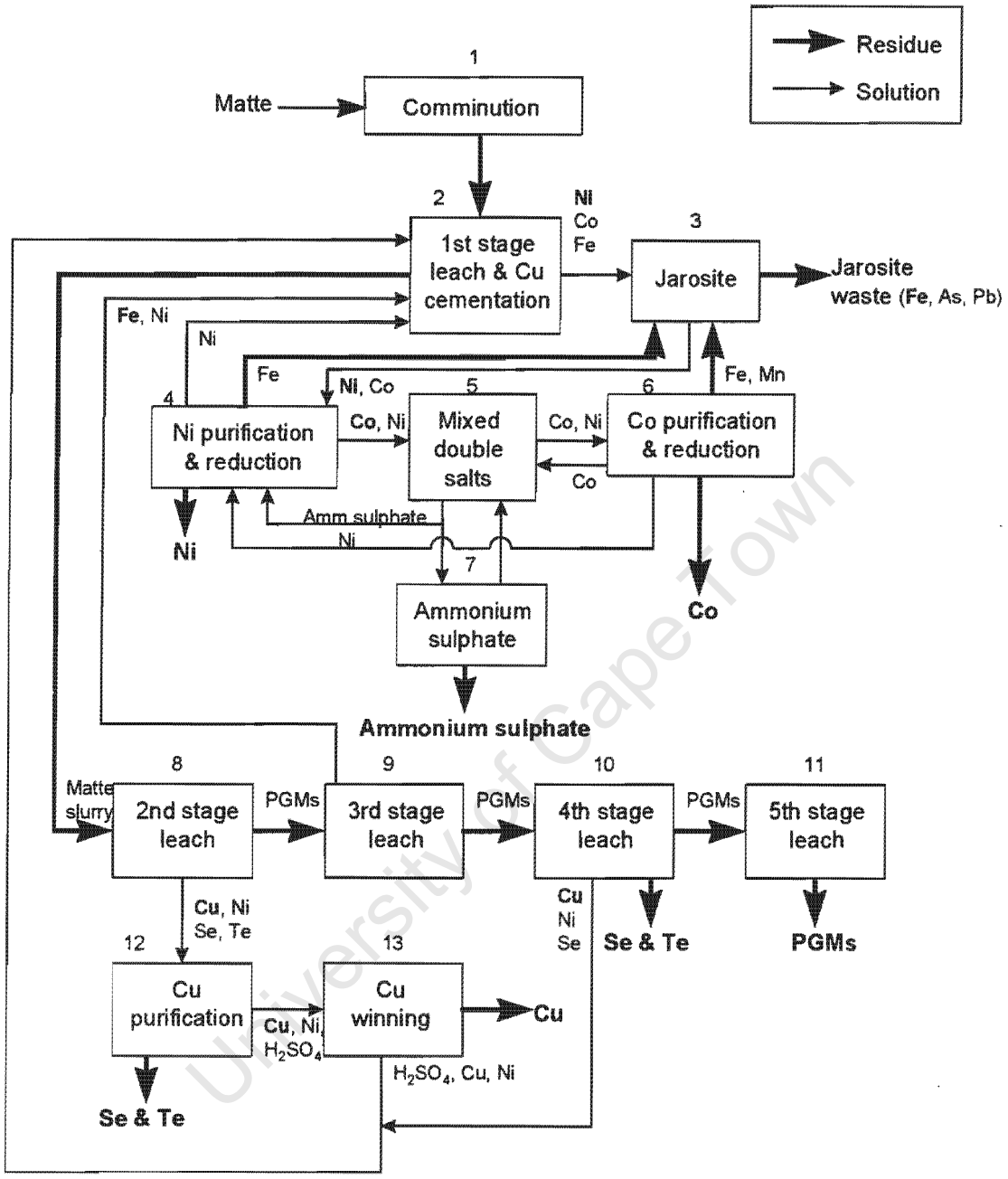


Figure 4.1: Simplified flowsheet for Impala Platinum Ltd's Base Metal Refinery, showing unit operations as defined for the LCI.

The BMR flowsheet, as depicted in Figure 4.1 was used to determine which streams were pertinent to this study, and thus which stream analyses were required for the elemental mass balances. Figure 4.2 shows more detail as to the inputs and outputs of individual unit operations.

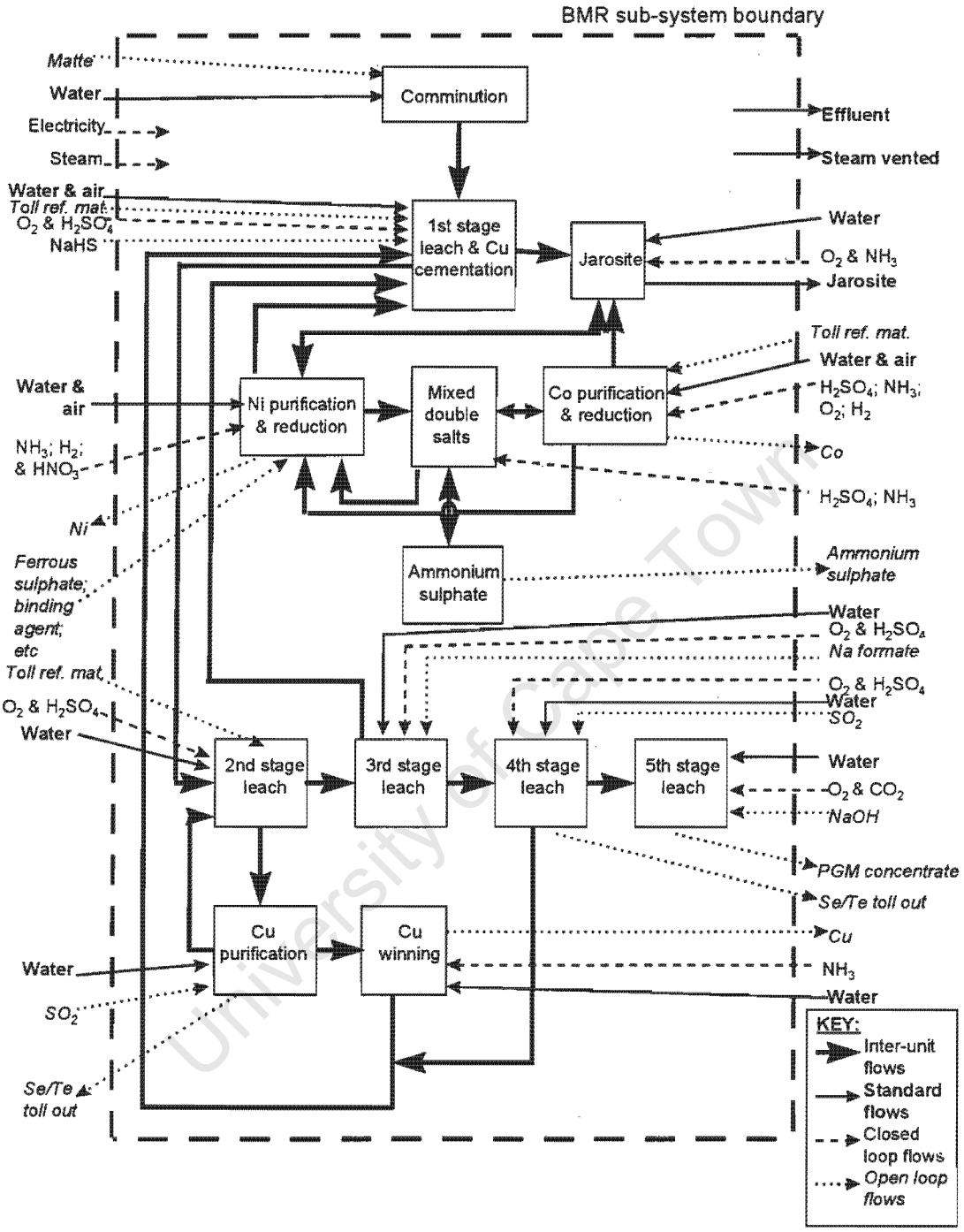


Figure 4.2: Flowsheet of Impala Platinum Ltd's Base Metal Refinery, showing inputs (raw materials and major reagents) and outputs.

4.3) SOURCES OF DATA AND THEIR RELATIVE ACCURACY

Monthly average data relating to Impala Platinum Ltd's BMR was collected for the period January 1995 to July 1997 inclusive, for reasons discussed in Section 3.3.

In order to ensure portability and simplicity, the databases were set up in the commercial spreadsheet programme Microsoft Excel version 7.0 for Windows 95, as this programme is widely used, is user-friendly, and is readily available via Impala's IT network. Excel has also been used in many other similar applications (Reuter, *et al*, 1995).

a) Data for the overall mass balances

Details regarding the inputs and outputs were obtained from a number of different sources, as follows.

Production records, as given in the Management Month-End Reports, served as a compilation of data from various sources (analyses, flowrates and mass measurements). Purchase records aided in the quantification of reagent inputs. Electricity, natural gas, and water are supplied to the BMR site and are charged for by utility companies. These inputs are thus metered, and the quantities used could be obtained from the records of these meter readings. Similarly, the volume of effluent which leaves the BMR site is monitored by means of a meter. The limited air emission monitoring reports which were available were also used.

Metal accounting and performance records, as well as process logsheets were used to obtain quantitative information for the mass balances. Transport data (in terms of actual delivery distances travelled) was obtained from the logsheets of the truck drivers. The sales and dispatch records of the Commercial Department were also utilised, with respect to toll refining information. Other qualitative and quantitative information was obtained from past and current employees. Finally, certain quantities were calculated when no hard data was available. Boiler emission calculations, for example, were based on coal and ash analyses. The accuracy relating to each calculation is given in the relevant section.

The environmental impacts relating to the reagents which were excluded from the LCI were obtained from Material Safety Data Sheets (MSDS), in order to prevent

severe negative impacts from being overlooked. The accuracy of toxicity data given in these is difficult to quantify, due to the incorporation of safety factors in the values. This uncertainty was not considered, however, as the MSDSs were used to obtain qualitative information in terms of possible significant environmental impacts.

The accuracy of data relates to the means of measurement employed in generating it. The weighing accuracy of matte and toll refining materials treated, for example, is governed by the accuracy of the scale used, which in the mass range of interest (500 - 2000kg per bag), has a relative error of 0.15%. Most of the other data was based on flowrates, as determined by meter measurements, which have a relative error of 5% or less. (The meters are calibrated every 6 months to ensure that this level of accuracy is maintained). Tank level measurements and weighbridge measurements relating to monthly reagent consumptions, have an error of less than 10%.

In the case of the measurement of transport distances, the variance due to variations in routes travelled and so on, is greater than the uncertainty in the distance measurement. Thus the error was estimated to be around 10% due to the variance. Similarly, for the addition of reagents from bags and drums, variations in the quantity of reagents used occur due to differences in initial content as well as the variation in the quantity of the reagent remaining in the container after use. After physical examination of some "empty" drums, this error was estimated to be below 2%.

b) Data for the elemental mass balances

The majority of the data used in the elemental mass balances was obtained from metal accounting analyses performed by Impala's Base Metal Laboratory (BML) (relative error of approximately 10%). Analyses of somewhat lower accuracy and precision, generated for process control purposes, were the secondary source of data (relative error of approximately 15%). The accuracy varies according to the sample matrix and the concentration of the analyte, with improved accuracy for analytes of higher concentrations. The use of multiple matrix matched calibration standards and quality control samples ensure that the accuracy remains at acceptable levels, according to the purpose of the analyses.

Other streams which are not routinely sampled, but which were necessary for mass

balance purposes, were sampled daily by the author over the period of a week, and submitted to the BML for analysis in the same manner as the metal accounting samples.

A number of non-routinely analysed components (sulphate, nitrate, sodium, potassium, calcium and magnesium) in waste streams (BMR effluent and jarosite waste) were also sampled and analysed, by Billiton Laboratories (now SGS Laboratories). The accuracy was in the same region as that obtained by the BML for metal accounting purposes (relative error of less than 10%).

Flowrates were obtained from actual data wherever possible, as described in (a) above (for matte and toll refining inputs, reagents, and products and by-products). The average flowrates of the remaining process streams (inter unit operation flows) were obtained by adjusting those used in the Metsim model of the BMR process, as will be discussed in more detail in section 4.7. The error in these values was estimated to be between 10 and 15%, based on the accuracy of the Metsim model.

c) Overall accuracy

The overall error was thus estimated to be between 10 and 15%. Both the overall input and output LCI mass balance and the elemental unit operation mass balance were verified by Senior BMR Project Engineers. It is acknowledged that higher errors were evident for some of the monthly LCI data, due to short-term faults with flowmeters and the like.

4.4) INPUTS TO THE BMR

Mass balances, with respect to the overall inputs to and outputs from the BMR process itself, and the ancillary steam and hydrogen generation processes, are given in Table 4.2, which represents the average of the monthly averages over the period considered. Sources of the data are included and tables relating to individual months are included in Appendix 1.

AVERAGE BMR PROCESS DATA:

INPUTS	t/mth	SOURCE
Raw materials		
Impala matte	1343	Ex month end reports
Other toll refining matte	152	Ex metal accounting
Ni sulphate	1124	Ex metal accounting
Co nitrate	118	Ex metal accounting
Liquid reagents		
H_2SO_4	1121	Ex bulk reagent records
HNO_3	61	Ex bulk reagent records
Ammonia	943	Ex bulk reagent records
Gaseous reagents		
Oxygen	1176	Ex bulk reagent records
N_2	557	Ex month end reports
Inter-unit flows		
Steam	32907	Ex steam data
Hydrogen used	71.7	Ex H_2 balance
CO_2 used	155	Ex H_2 balance
Standard flows		
Water	20391	Ex water balance
TOTAL INPUTS	**60120**	t
OUTPUTS		
Main product		
Gross Ni produced	**966.5**	Ex month end reports
By-products		
Cu cathode	412	Ex month end reports
Co powder	7.22	Ex month end reports
Ammonium sulphate	2592	Ex month end reports
Se/Te solids	2.88	Ex Commercial Department
PGM concentrate	2.84	Ex metal accounting
PGM solution	29.9	Ex metal accounting
Wastes		
Jarosite	56.7	Ex metal accounting
Effluent	12716	Ex water balance
Standard flows		
N_2 vented	557	As above
Steam vented	16298	Ex water balance
Cooling water losses	11240	Ex water balance
Other open loop flows		
Demin to PMR	910	Ex logsheet
Water to sewer	7548	Ex logsheet
TOTAL OUTPUTS	**53339**	t
INPUTS-OUTPUTS	**6781**	t
% ERROR	**11**	

AVERAGE STEAM GENERATION DATA:

INPUTS	t/mth	SOURCE
Coal	5411	Ex month end reports
Oxygen (from air)	11827	Calculated
Boiler feed water	40249	Ex process records
Water to ash	410	34.5% moisture
TOTAL INPUTS	**67897**	t
OUTPUTS		
Ash (dry)	779	Calculated
H_2O in ash	410	34.5% moisture
SO_2	38	Calculated
CO_2	13887	Calculated
H_2O vapour	2314	Calculated
NO_2	220	Calculated
Effluent	750	Estimated by process staff
Steam to PMR	1895	Ex process records
Steam to H_2	4589	Ex process records for 05/97
Steam to BMR	32907	By difference (prod-H_2-PMR)
Thus steam loss at boilers	108	Calculated via bal. closure
TOTAL OUTPUTS	**57897**	t
INPUTS-OUTPUTS	**0**	

AVERAGE HYDROGEN GENERATION DATA:

	t/mth	SOURCE
INPUTS		
Natural gas (feed)	307	Calculated
Steam (incl. heating)	4589	Ex process records for 05/97
Inputs for heating:		
Natural gas (fuel)	297	Calculated
Oxygen (from air)	631	Calculated
TOTAL INPUTS	**5824**	t
OUTPUTS		
Steam loss	4297	Calculated via bal. closure
H_2 PMR	0.8	Estimated by process staff
H_2 vented	9.00	Ex production performance report
H_2 BMR	71.7	By difference (total ex month end reports less H_2 PMR less H_2 vented)
CO_2 BMR	155	Assume 30% is used
CO_2 vented	362	Assume 70% is vented
Outputs ex heating:		
CO_2	501	Calculated
H_2O vapour	401	Calculated
N_2	27	Calculated
TOTAL OUTPUTS	**5824**	t
INPUTS-OUTPUTS	**0**	

TOTAL ENERGY IN		
Electricity	6466442	kWh ex meter readings

Table 4.2: Average of monthly inputs and outputs for the BMR, for the period 01/95 to 07/97 inclusive.

The various inputs and outputs will now be briefly discussed.

A) BMR PROCESS INPUTS:

4.4.1) Matte and toll refining material inputs:

All matte and toll refining material is bagged and transported to the BMR site by road in trucks or containers (for those which originate overseas). The Impala matte is transported approximately 200km from Mineral Processes to the BMR. As is consistent with the boundary drawn in section 3.3, the transportation of these materials to the BMR site is excluded from the LCI. The activity of base metal refining is considered, and the source of materials is not fixed. The bags used to transport each of these materials are recycled.

The average monthly analyses of the matte and toll refining materials are detailed in the section on elemental mass balances (section 4.7). On average (01/95 - 07/97) the Impala matte (which is currently the primary source of base metals) contained 49% Ni, 29% Cu, 0.3% Co, 20% S, and 0.6% Fe. The other toll refining materials are other mattes, nickel sulphate and cobalt nitrate. The quantities processed per month varied significantly, and the composition was dependent to some extent on the source of the material.

4.4.2) Liquid reagents:

The major uses of the reagents are given in section 2.4. All three of the liquid reagents included in the LCI are obtained in bulk from suppliers due to the large quantities used. The transportation distances were excluded from the initial LCI, but formed part of the sensitivity analysis (refer to section 6.2.1).

Sulphuric acid is delivered to the BMR site in 20 or 30kℓ tankers (the transportation distance is 100km for a round trip). It is one of the major reagent inputs of the BMR process (for use both in the BMR process itself, and in the regeneration of the resin used for water demineralisation), with an average usage for the period considered of 1121t/month.

The transportation distance for **nitric acid** is 380km (for a round trip), and 70% of the capacity of a road tanker is utilised. On average 61t is used per month, primarily for leaching Ni deposits off the internals of the Ni reduction autoclaves.

Ammonia is delivered (130km round trip), by road tanker (at 90% capacity). The average monthly consumption was 943t.

4.4.3) Gaseous reagents

Oxygen is used as an oxidant (average monthly consumption of 1176t), while **nitrogen** is used to provide an inert atmosphere (557t/month is used on average).

4.4.4) Inter-unit and standard flows

The inter-unit and water flows will be discussed under the steam and hydrogen generation subsections, and the water balance respectively.

B) STEAM GENERATION DATA:

For the time period considered, an average of 5411t of **coal** was burnt by the boilers per month. B-grade, pea size (-25+6.3mm) coal, which has a fines (<4mm) content of less than 12.2%, is used in the boilers. The calorific value of the coal is determined periodically, and was approximately 27MJ/kg, while the ash content of the coal was approximately 14.4% (incombustible material), and the moisture content 4.6%. The coal contained 27% volatile matter (inherent combustible gases, which allow for good ignition properties) and had a total carbon content of 70.0%. The sulphur content was approximately 0.35%, while the H content was 4.24%, the N 1.24%, and the O 5.18%.

These values were used to calculate the **oxygen** (provided primarily by atmospheric oxygen, as well as by the oxygen present in the coal itself) required to burn the coal (100% combustion was assumed). The excess oxygen (or air) was not included, as the use of atmospheric air does not contribute to any of the impact categories as defined in the PEMS software, thus it would not affect the environmental profile. Excess air would be vented via the stack, and these emissions are also not included. The gaseous emissions (SO_2, CO_2, H_2O, and NO_2) were calculated from the average coal composition (minimal sulphur (approximately 0.1%) and carbon remains in the ash). The accuracy of these calculations (as shown in Appendix 2) is estimated to be within 15% (based on the fluctuations in the coal composition and combustion efficiencies). The operation of the boilers will be discussed in more detail in section 4.6.5.

Boiler feed **water** (on average 40249m^3/mth) is supplied by the demin plants and from recycled plant condensates, for use in steam generation. Water is also added to the ash.

C. HYDROGEN GENERATION DATA:

Hydrogen rich Sasol gas is obtained by pipeline (primarily from Sasol's Sasolburg plant), where it is produced from coal. A typical gas analysis is given in Table 4.3.

COMPONENT	MOLE %
H_2	43.01
CH_4	28.83
CO	18.03
N_2	4.45
C_2H_4	0.05
C_2H_6	0.39
Ar	0.47
C_3H_6	0.12
CO_2	4.24
C_3H_8	0.16
C_4H_8	0.07
C_4H_{10}	0.09
C_5H_{10}	0.01
C_5H_{12}	0.06

Table 4.3: Typical hydrogen-rich Sasol gas composition (12/1997).

Note: The mole percentages of the longer chain hydrocarbons (C_nH_n) were added to that of methane for calculation purposes, because they are present in low concentrations in the feed gas (less than 3% by mass in total) and because their relative quantities vary.

The gas is used at Impala as a reactant in the production of hydrogen via the water-gas shift reaction, as well as a fuel which is combusted to provide heat for the hydrogen plant. The entire quantity of fuel gas was ascribed to the hydrogen plant, although a relatively small amount is used as a fuel by the Ni furnaces, which is not

metered. In any event, the two usages would be summed for the overall LCI, thus the same overall results would be produced as if the two usages had been separated.

The atmospheric **oxygen** required for this combustion reaction was calculated from the gas composition, as obtained from Sasol, with the combustion products being CO_2, H_2O (vapour), and N_2 (refer to Appendix 2 for the monthly mass balances, and calculation details). The composition of the gas does vary to some extent, but the values as shown in Table 4.3 are assumed to be suitable averages. The error in these calculations should be less than 15%, as they were based on stoichiometric calculations and100% combustion efficiency was assumed.

The **steam** required for both the shift reaction itself and for heating purposes, as obtained upon summation of the daily logsheets for the month of 05/97, was used as an average value for each month. This was confirmed to be a suitable assumption upon comparison with the quantities used for other months. In addition, the steam used by the BMR process was calculated by difference from the total steam consumption and this hydrogen generation consumption, thus the overall usage would remain the same.

The Sasol gas used to produce hydrogen and carbon dioxide is desulphurised utilising activated carbon and is then catalytically reformed at a temperature of around 850°C to almost 100% conversion of the methane, according to the endothermic reaction:

$$2CH_4 + 3H_2O \rightarrow 7H_2 + CO_2 + CO$$

The product gas is cooled, and then passed through a high temperature shift (HTS) converter (at approximately 380°C), and then through another shift converter at a lower temperature (LTS) (around 230°C). The following exothermic reaction occurs in these converters, in the presence of catalyst:

$$CO + H_2O \rightarrow H_2 + CO_2$$

The CO concentration is reduced in this manner to less than 3% in the HTS, and then to less than 0.3% in the LTS.

The hydrogen and carbon dioxide mixture is separated using monoethanolamine (MEA), which absorbs 99.9% of the carbon dioxide and is later regenerated with steam. The absorber unit is protected from corrosion by the addition of sodium metavanadate or Helamin (refer to section E to follow).

Removal of remaining traces of carbon monoxide and carbon dioxide from the hydrogen is necessary as these impurities reduce the ease with which the nickel powder is reduced by the hydrogen reduction process. Carbon monoxide and dioxide are thus removed by methanation at approximately 300°C, according to the following exothermic reactions:

$$CO + 3H_2 \rightarrow CH_4 + H_2O$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

The purity of the hydrogen produced ranges from 97-99% (it contains only 0.5% methane).

On average (01/95 to 07/97, inclusive), 9807GJ of hydrogen-rich Sasol gas was used as fuel gas, while 10138GJ was used as feed gas, to produce 82t of hydrogen per month, of which 9t was vented.

D. ELECTRICITY:

Impala is provided with 44kV electricity from Eskom, which is then stepped down on site as required. In 1997, Eskom generated 170464 GWh of electricity from 90 million tons of coal, which equates to 0.528kg coal burnt for every kWh of electricity generated (Eskom is the single biggest consumer of coal in South Africa). The overall water consumption was 1.3ℓ/kWh (Eskom, 1997). It was noted that this water consumption is strongly influenced by the prevailing atmospheric conditions, particularly at the wet-cooled power stations. Further reductions in water consumption are only deemed possible by the development of dry-cooled power stations, or by modifications to the energy mix (such as nuclear or hydro-electric power stations).

With respect to Impala's BMR, the average monthly electricity consumptions of the various sections of the BMR, including Utilities, are summarised in Table 4.4. The

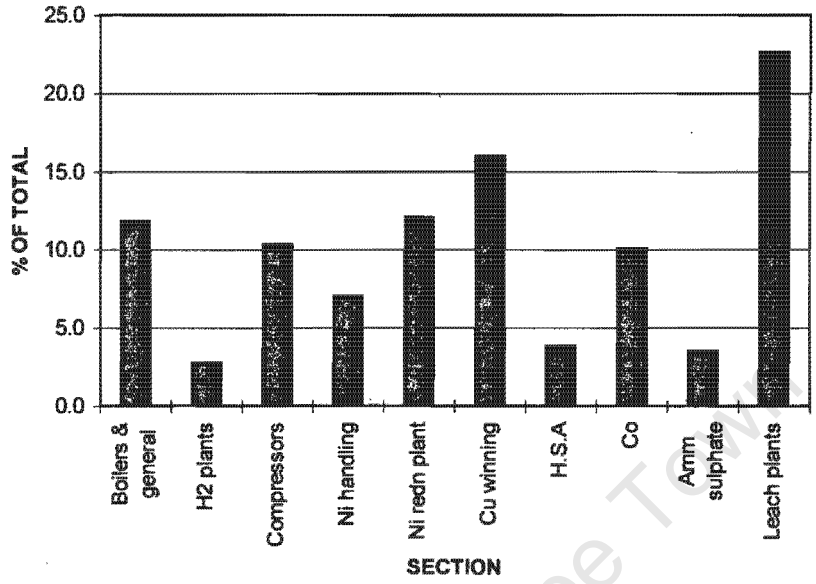
averages were obtained from monthly electricity meter data, taken over the period from the 06/95 to the 07/97 inclusive (data prior to 06/95 was unavailable). The average consumption is given for each section in kWh, as well as the percentage contribution of this consumption to the total BMR consumption. The latter is shown graphically in Figure 4.3. The unit operations (refer to Table 4.1), to which each section relates are also given in Table 4.4.

SECTION	UNIT OP.	AVG kWh/ month	% RSD	AVG % OF TOTAL
UTILITIES				
Boilers & general		761583	13.7	11.8
H_2 plants		175944	32.8	2.7
Compressors		669060	23.0	10.3
TOTAL		**1606587**		**24.8**
BMR				
Leach plants etc	1, 2, 3, 5, 8 & 12	1464918	8.1	22.7
Ni handling	4	455012	17.0	7.0
Ni redn plant	4	780126	16.8	12.1
Cu winning	13	1032599	16.8	16.0
H.S.A.	9,10 &11	247572	4.9	3.8
Co	6	651345	10.4	10.1
Amm sulphate	7	228283	11.8	3.5
TOTAL		**4859855**		**75.2**
OVERALL TOTAL		**6466442**		**100**

Table 4.4: Average monthly electricity consumption of BMR sections, in kWh and as a percentage of the total BMR consumption.

From the data given in Table 4.4 and Figure 4.3, it is evident that the copper winning section consumes a significant portion of the electricity (16%), as would be expected. The average percentage current efficiency of the copper electrowinning process was 75% over the period 01/95-07/97 (calculated by dividing the actual mass of copper produced by the theoretical production derived from Faraday's Law).

Figure 4.3: Relative electricity consumptions



The boilers (including general electricity usage) and compressors of the Utilities section are also relatively energy intensive operations (11.8 and 10.3% respectively). The high energy consumption of the leach plants category reflects the energy used by the ball mills during comminution, as well as by agitators and feed pumps in the other included unit operations. The Ni reduction and handling consumptions and cobalt plant consist mainly of energy usage by agitators and pumps. Similarly, a relatively small amount of electricity is utilised by the H.S.A. (3rd, 4th, and 5th stage leaches) and ammonium sulphate sections.

The high percentage relative standard deviations, especially for the Utilities sections, reflect the variations in demand for their products (for example, steam), and thus the quantity of electricity they consume.

As can be seen from Table 4.4 some of the sections relate to more than one unit operation, due to the present metering structure. Further apportioning of the values between the unit operations would incur significant errors, due to a current lack of information regarding the energy usage of individual processes, thus this was avoided.

E. EXCLUDED REAGENTS:

Reagents which were not included in the LCI, due to the constraints given in section 3.3, are listed in Table 4.5. The use of each reagent in the BMR processes, and the approximate average quantity used per month are included. The accuracy of the consumption figures for these reagents are generally considerably lower than those for the reagents included in the LCI. Many of them were estimated by plant personnel. Actual consumption figures are not recorded, as they are not performance indicators. The excluded reagents (excluding the demin resins, the hydrogen plant catalysts and carbon, the analytical reagents and the air used) represent <0.2% of the total reagent input.

The reagents will be discussed with respect to specific environmental concerns relating to their use, although the impacts associated with their manufacture should also be borne in mind. Many of these are proprietary processes, thus such information is difficult to obtain. The information was taken from Material Safety Data Sheets (MSDSs), as obtained from reagent suppliers or from the Australian Health ChemAlert version II software package. Information relating to environmental effects is primarily considered, as the human toxicity issues are generally well addressed by occupational health programmes.

Sulphur dioxide is transported to the BMR site by road tanker. The average monthly consumption for the period considered was 27t. The production method involves the roasting of sulphur ores to produce sulphur dioxide gas, which may then be further reacted to produce sulphuric acid, via the Contact Process (Austin, 1984):

$$S\ (\ell) + O_2(g) \rightarrow SO_2(g) \qquad \Delta H = -298.3kJ,\ 25^{\circ}C$$

$$SO_2(g) + \tfrac{1}{2}O_2(g) \leftrightarrow SO_3(g) \qquad \Delta H = -98.3kJ,\ 25^{\circ}C$$

$$SO_3(g) + H_2O(\ell) \rightarrow H_2SO_4(\ell) \qquad \Delta H = -130.4kJ,\ 25^{\circ}C$$

The major environmental impact associated with sulphur dioxide use, is that of fugitive emissions, which could lead to acid rain and cause toxicity problems.

REAGENT	USE	QUANTITY USED PER MONTH
SO_2	Se/Te precipitation	27t
NaCl	Demin regen	50kg
Demin resins	Demin	(replaced every 10yrs or so)
NaOH	Demin regen & 5th stage leach	23t
Anikem 7330	Micobiocide for cooling water (a)	400kg
Anikem 8365	Corrosion inhibitor for cooling water (b)	226kg
Anikem 2820	Cooling water treatment (c)	520kg
Helamin	Boiler water treatment (d)	238kg
Flocon 100	RO water treatment (e)	161kg
Na metabisulphite	RO plant cleaning	16kg
EDTA	RO plant cleaning	40kg
HCl	RO plant cleaning	5.8kg
Monoethanolamine	H_2 plant CO_2 removal	896kg
Helamin	Corrosion inhibitor in amine section of H_2	4kg
Sodium metavanadate	Corrosion inhibitor in amine section of H_2	400g
Catalysts	H_2 plant (f)	18000ℓ replaced every 5yrs
Carbon	H_2 plant C-traps	3000ℓ replaced every 3-5yrs
Dicalite filter aid	Co & Ni reductions	1t
Sodium formate	3rd stage leach	12.39t
NaHS	Cu cementation	4400kg
Lab chemicals (various)	Analyses	Unknown
Compressed air	Tank pressurisation	2890000Nm^3
N9300 modifier	Surfactant used in Ni reduction	600kg
Ferrous sulphate	Ni reduction: cat. & nucleation agent	1t
Acrysol	Binding agent for Ni briquettes (g)	6t
Anthraquinone	Nucleation reagent, Ni	50kg
Ammonium hydroxide	Ammoniation of acrysol & N9300	4t
Aerosol C-61	Surfactant used in Ni nucleation	0.1kg
Bevaloid antifoam	Antifoam	200kg
Na sulphide	Nucleation reagent, Co	10kg
Na cyanide	Nucleation reagent, Co	50kg

Table 4.5: Reagents excluded from the LCI.

(a) an aqueous solution of substituted isothiazolinone
(b) an aqueous solution of phosphonate, sulfonated acrylate polymer & substituted triazole
(c) an aqueous solution of sodium tetraborate, sodium phosphonate, sodium molybdate, sodium hydroxide & a substituted triazole
(d) polyalkylamines & polyacrylates in water
(e) an aqueous soln of polyacrylic acids
(f) NiO; Fe_2O_3; Cr_2O_3; CuO; ZnO; Al_2O_3
(g) a polyacrylic acid

Demin regeneration reagents which are used in relatively small quantities (NaOH and NaCℓ) were excluded from the LCI, as were the resins used (which have long life spans). Further details regarding the demin plants are given in section 4.6.3. The MSDS for NaOH noted that should it enter an aquatic system, it could cause fish mortalities due to the increase in pH. It can also seep into groundwater.

Cooling and boiler water treatment chemicals are administered to the circuits by outside companies, as discussed in sections 4.6.5 and 4.6.6. The compositions of these compounds, which are used to prevent corrosion and bacteriological growth, are given in the notes to Table 4.5. The MSDS for Helamin indicated that this mixture has an LD_{50} >2000mg/kg in rats with respect to acute oral toxicity, and is classified as only a slight danger to water, in terms of toxicity to fish (striped mullet) and Daphnia. The biodegradability of the mixture was >54%, but the product is retained by silicate containing soils.

A number of toxicological studies (on rats, rabbits, guinea pigs, humans, and dogs) have been conducted with respect to Anikem 7330, as indicated on the MSDS. The acute oral toxicity to rats was 3810mg/kg. This product is toxic to fish (it contains cupric nitrate), thus it should not be discharged into waterways, although the aquatic toxicity rating is only given as moderate on the MSDS. Anikem 7330 is classified as a hazardous waste.

Anikem 8365 is a corrosion deposit inhibitor. None of the ingredients are given as being of concern with respect to water or air pollution. Anikem 2820 is classified as a hazardous waste, and of concern with respect to water pollution on the MSDS, due to its caustic soda content.

Small quantities of these boiler and cooling water treatment chemicals would enter the effluent pond upon blowdowns of the respective systems. Currently, they could ultimately enter the groundwater system upon usage of this effluent by Ergo in the reclamation of slimes dams. This is undesirable, when the toxicological information regarding these chemicals, as given above, is considered, although they would be present at very low concentrations due to the effect of dilution. The effluent disposal/treatment options are currently being evaluated, however, and thus this potential source of pollution will shortly be controlled (refer to Chapter 9).

Reverse osmosis (RO) plant chemical usage:

Flocon 100 is used to treat the RO water. It has an acute oral LD_{50} of >5000mg/kg in rats, and ecological toxicity information (with respect to fish and birds) indicate that it should be disposed of with care. Ethylenediaminetetraacetic acid (EDTA), which is used to clean the RO membranes, should not be disposed of into watercourses, as it can be toxic to aquatic ecosystems. In the environment, hydrochloric acid (which is also used by the RO plants) may infiltrate into the groundwater causing contamination (although some neutralisation by reaction with carbonates in the soil would occur). A portion of these chemicals would currently enter the effluent pond, and the remainder would be recirculated within the BMR with the RO plant products (treated water and brine).

Hydrogen generation plant reagents:

Monoethanolamine (MEA) may cause severe damage to aquatic life should it enter water courses (although it is contained within the hydrogen plant under normal operations), and sodium metavanadate is highly toxic to aquatic organisms. The oral LD_{50} in mice for this compound is 75mg/kg (as given on the MSDS). Helamin, which is used as a corrosion inhibitor in the MEA circuit, in conjunction with sodium metavanadate, has already been discussed. These chemicals are currently contained within the hydrogen plant boundaries.

Hydrogen plant catalysts:

Nickel and cobalt are efficient catalysts in the hydrogenation of carbon monoxide to methane. It is necessary to deposit the metal on a carrier in order to increase the surface area, and to prevent the sintering of the catalyst. Magnesium and aluminium oxide are the most commonly used carriers (Van de Venter, 1993). Excess steam is used in order to minimise the decomposition of feed gas to carbon and hydrogen, which results in the poisoning of the catalyst with carbon. The catalyst can be regenerated with steam and air, in order to burn off the carbon. Sulphur also poisons the catalysts, thus it is removed from the feed gas by a carbon trap. The hydrogen catalysts used at Impala therefore last approximately five years. Spent catalysts are disposed of by Enviroserve at the Holfontein Class H landfill site (a site suitable for hazardous waste disposal).

Sodium formate, which is used as a reductant in the third stage leach (refer to section 2.4, specifically reaction 17) reacts to form carbon dioxide, which would be

vented (these air emissions were also excluded from the LCI). (The use of sodium formate has since been optimised, thus the consumption has been substantially reduced). **NaHS** is used as a reductant in copper cementation and the average monthly consumption of NaHS is 4.4t. The most common production method involves the treatment of sodium hydroxide solution with hydrogen sulphide, which has the obvious potential environmental impact associated with fugitive H_2S emissions (Austin, 1984).

The **Bevaloid antifoam** (which is a blend of silicone fluids and synthetic emulsifiers), is non-biodegradable and could bioaccumulate. **Dicalite filter aid** is derived from volcanic rock and is non-toxic and inert. Relatively small quantities of a large number of **chemicals** are utilised in the **analysis** of the process streams. The major chemicals used in the BML are hydrochloric acid (200-300ℓ per month) and nitric acid (50-75ℓ per month). The effluent from the laboratory is routed to the process. The **air** consumption indicates compressed air usage by various tanks and vessels within the BMR (on average 35t/mth of air compressed to 1.1MPa, and 1t/mth of air at 600kPa is used). It is excluded from the LCI, as the air which is subsequently vented is excluded as well, although it is acknowledged that oxygen would be depleted from the compressed air when it is used for leaching purposes (also note that mostly pure oxygen is used for this purpose, which is included in the LCI). This exclusion is deemed acceptable because the use of air does not contribute to any of the environmental profile scores as determined by the PEMS software.

A mixture of reagents is used in the **reduction of nickel**, where they serve as catalysts, nucleation agents and surfactants. They form part of the ferrous iron slurry as explained in section 2.4. The environmental effects of ammonium hydroxide derive from those of ammonia. Upon rain wash-out any atmospheric ammonia derived from fugitive emissions, is returned to the soil where it is strongly adsorbed. In water, ammonium ions are rapidly converted to nitrates, causing an increase in pH and biological oxygen demand. Ammonia is highly toxic to fish: 1ppm in water is fatal to some species. Most of the other compounds and mixtures used are toxic to aquatic ecosystems. Ferrous sulphate, for example, has a lethal dose of 100ppm/4 hours to bass. Some of the organic compounds used during nickel reduction would be entrained in the nickel product (and may then be removed

during sintering of briquettes). The remainder of the compounds present in the reduction end solution is recycled within the BMR process. The iron sulphate would thus be purged via the jarosite process.

The **nucleation agents for cobalt** include the use of sodium cyanide, which is highly toxic to humans, plants, and animals. Concentrations in aquatic systems of above 0.07ppm are toxic, while that for livestock is 0.02ppm. In water, the cyanide oxides will decompose slowly to cyanate, which dissociates to carbon dioxide and nitrogen, thus biodegradation may occur. Other reactions may lead to the production of toxic hydrogen cyanide gas, or metal cyanide complexes may form if these elements are present in the water. The use of this chemical is strictly controlled in the BMR to ensure that accidents and spills do not occur.

4.5) OUTPUTS FROM THE BMR

Specific outputs will now be discussed. For details on the output quantities, refer to Table 4.2 and Appendix 1. Outputs from individual unit operations are shown in Figure 4.2. Analyses of the major components in the output streams are noted, and full details may be found in the elemental mass balances (section 4.7).

A) BMR PROCESS OUTPUTS

4.5.1) Products:

a) Nickel:

Nickel is the major product of the BMR, both in terms of revenue generation and quantity produced, with an average production of 967t/month (for the period 01/95 to 07/97 inclusive). The average purity of the sintered nickel briquettes (average production of 585t/mth) was 99.86% (%RSD of 0.01), while that for the unsintered briquettes and nickel powder was 99.81% (0.02% RSD) and 99.85% (0.03% RSD), respectively. The air emissions of CO_2 and H_2S from the sintering operation are relatively small and are not quantified. They were therefore excluded from the LCI. The nickel briquettes are transported in bulk by truck or are drummed. (Together with drummed cobalt powder, less than 300 drums are used per month). The bulk of the nickel produced is sold to the steel and foundry industries (Impala Platinum Ltd, 1980).

The versatility of nickel is a consequence of its properties: it has a high melting point; it readily forms alloys with other elements; it forms an adherent oxide film and is resistant to corrosion by alkalis; it is catalytically active; it is readily deposited by electroplating; it is readily deformable; and it is ferromagnetic at room temperature (Cutler, 1997).

Nickel is therefore used in plating; rechargeable Ni/Cd batteries; and hydrogenation catalysts (Hayes, 1997). Nickel-bearing alloys include stainless steels, which consume approximately 60% of the global nickel production (in which Ni improves corrosion-resistance and workability) and nickel-iron alloys which are used where low thermal-expansion is important. Copper-nickel alloys are used in coinage, and high nickel alloys are used in gas turbines for aircraft and power generation. Nickel-containing alloys are readily recycled, thus over half of the input to the stainless steel industry is recycled scrap (Cutler, 1997).

b) Copper:

Copper is produced in the form of cathodes, which are baled prior to dispatch to customers. The average monthly copper production was 412t for the period considered (the average purity was 99.87%, with a %RSD of 0.06). Most of the copper produced is sold on the European market. It is used in the manufacture of electric wires and cables, pipes, and sheets, and as a component of brass, bronze, and other alloys (Impala Platinum Ltd, 1980). Copper chemicals include catalysts, fungicides and wood preservatives.

There are a number of pressures on the copper market. The use of copper in the telecommunications industry, for example, is threatened by increasing use of fibre optics and aluminium is a rival to copper for use in electrical and mechanical applications. Construction, which is copper's largest non-electrical outlet, is facing competition from plastics (Ayres, 1996). Markets for copper in China and Asia are growing, but substitution and legislatory limitations to usage are putting pressure on the copper market (Thompson, 1997).

c) Cobalt:

Cobalt is produced as a powder, and is drummed prior to dispatch. The average cobalt production for the period considered in this case study was 7t/month (the

average purity was 99.89%, with a %RSD of 0.06). The major use of cobalt is in the aerospace and battery industries, thus the cobalt market is related to the demands by these sectors. Cobalt is also used in steel, catalysts, paint dryers, pigments, and magnets (Hawkins, 1997).

4.5.2) Ammonium sulphate:

The production of ammonium sulphate is the primary means of purging sulphur from the BMR process, although a small quantity of sulphur also leaves the plant in the effluent, and in the jarosite residue. The average production of ammonium sulphate for the period considered in this case study was 2592 t/month (refer to Table 4.2), and the average purity was 97% (2.5% RSD, due to variation in Na, Ni, Cu and Co content. For average values, refer to the elemental mass balance and the corresponding data in Appendix 3. This product is sold for use as fertiliser, and is thus classified as a byproduct (an open loop output). The metal impurities in the ammonium sulphate would be absorbed by the crops, or immobilised by the soil. Alternatively, they may seep into groundwater.

An alternative to ammonium sulphate fertiliser production, is the generation and subsequent recycle of ammonia by means of a lime boil (Plasket and Romanchuk, 1978). The reaction of interest is:

$$Ca(OH)_2 + (NH_4)_2SO_4 \rightarrow CaSO_4.2H_2O + 2NH_3$$

Such a lime boil process was performed by Impala prior to 1988, where firstly all and later part of the ammonium sulphate purge stream was converted to ammonia, for re-use in the BMR process (Ireland, 1979). The drawbacks of the lime boil process included poor efficiencies and high ammonia losses, although the largest problem was the choking of the pipeline which transported the gypsum to the slimes dam for disposal (Gaylard, 1998b). When the BMR was extended, the production of ammonium sulphate for sale as fertiliser became economical, which had the subsequent advantage of eliminating gypsum waste generation. The lime boil process continued to be operated on a small scale, as a purge for contaminants (mainly for sodium and chloride ions), until in 1988 it was decommissioned when a chloride purge was introduced.

Impala's BMR has changed its technology choice for sulphur removal from a process which generated a large amount of waste (gypsum) which had to be

disposed of, to a process which produces a valuable by-product (ammonium sulphate) and which efficiently purges sulphur from the process.

4.5.3) Selenium/Tellurium Residue:

Selenium and tellurium are purged from the BMR process in the form of a residue (refer to section 2.4), which is toll refined for the recovery of these elements by an overseas company. 40% of the total world selenium demand is by the glass industry, as Se decolourises the green tint caused by iron impurities in glass bottles, and it is used in conjunction with other metals to colour glass. Se compounds are also used as highly stable red pigments in the plastics and ceramics industries (Union Minière, 1996).

High purity Se and its alloys are used as photoreceptors in plain-paper copiers, as well as rectifiers, carbon dioxide laser windows, voltage surge protection devices, infrared detectors and in photovoltaic cells and X-ray receptors in the medical field. Se may be added to carbon steel, stainless steel and copper, in order to improve machinability. It is an essential trace element and thus may be added to animal feed, while medicinal uses of Se include its use as a fungicide in the control of dandruff and dermatitis. Se is also used as a component of catalysts which are used for selective oxidation reactions.

The major use of Te is as an alloying element, as it improves machinability. In addition, it is used in the rubber industry as a vulcanising agent and an accelerator. Te is used in radiation detectors, in glass and ceramic pigments, and as an alloying component in Se photoreceptors.

In August 1991, the Agency for Toxic Substances and Disease Registry (ATSDR) of America, made available toxicological information regarding selenium. As a consequence of this, Van Der Vyver (1993) noted that it is therefore likely that the use of Se in some applications will be phased out, and it will be replaced by other metals.

4.5.4) PGM concentrate:

The PGM concentrate is transferred to the PMR for further refining as outlined in section 2.3.

4.5.5) Jarosite:

The jarosite process is used to remove iron, arsenic and lead from first stage leach liquor, in order to produce a cleaner and more filterable solution (Plasket & Dunn, 1986a) (Refer to section 2.4). On average 57t of jarosite is produced per month, with an approximate composition of 36% Fe, 0.15% Pb, 1% As, and 3.5% Ni. It is classified as a hazardous waste because of its lead and arsenic content, and is thus disposed of in a class H:H landfill site. Due to the hazardous nature of this waste, a number of issues relating to its generation and disposal will now be discussed.

a) Process options

Previously, an oxidation-hydrolysis process was used by Impala. The Fe-As residue thus formed (consisting of ferric hydroxide and ferric arsenate $Fe_2(AsO_4)_3$), was a collector of other minor impurities, such as Pb, Se and Te. The other advantages included operation at atmospheric pressure; reduction of the iron concentration to approximately 5ppm and the arsenic concentration to 1ppm, and the production of an easily filterable residue.

The disadvantages of the process were rather considerable, however: if the pH was not carefully controlled, co-precipitation of Ni and Co would occur. The solids thus had to be recycled to the smelter, which incurred costs, losses, and increased pipeline. Another negative consequence of this closed loop was that lead and arsenic accumulated in the overall metallurgical circuit.

The jarosite process was therefore tested and then implemented as an alternative. The jarosite residue contains less Ni and Co, it readily settles, and can be easily filtered and washed. The reactions also take place in acidic medium, thus recycling within the BMR process is facilitated. The haematite process (Fe_2O_3 precipitation) was another option. Higher temperatures are required, however, and the residue which is produced is difficult to filter and has poorer settling properties than jarosite. Haematite also has better impurity collection characteristics, which consequently leads to more nickel and cobalt reporting to the residue (Hofirek and Kerfoot, 1992).

b) Possible uses of jarosite

As vast quantities of jarosite are produced world-wide (particularly by the zinc industry), various means of utilising this material have been investigated (Dutrizac, 1983). These include thermal decomposition of the jarosite, to produce Fe_2O_3, for

use in the pigment or metal industries. Ammonia can also be recovered from the gases evolved at low temperatures prior to sulphur dioxide evolution. Calcination involves high energy costs, however, and the iron oxide produced may be contaminated with other metals. The ammonium ions present in the jarosite are potentially useful as a fertiliser with the added advantage of slow release of iron and trace metals into the soil. However, the presence of toxic elements (for example, arsenic), prevent its use. For the same reason, other miscellaneous applications, such as its use in cement manufacture, have also not been explored commercially. The jarosite residue produced by Impala is thus disposed of.

c) Disposal site details

Audits of the relevant landfill site (Enviroserve's Holfontein Class H:H site) are performed annually. Safe disposal certificates are obtained from Enviroserve for each dispatch, which indicate that the jarosite is treated with ferrous sulphate (due to the presence of arsenic in the residue) and lime (to immobilise the nickel), and is then disposed of in a designated cell on the site. In this manner, the waste is disposed of in accordance with legal provisions.

Currently, a total of 20000 t/month of waste is disposed of at the Holfontein site, of which 12000t/month is hazardous waste, 3000t/month is liquid waste, and the remainder is Municipal waste (Gombault, 1998). The jarosite is thus co-disposed with a vast variety of wastes, and at different depths. Waste is treated to pH 9 prior to disposal, which results in the production of a leachate which has a pH of 7.2 on average, due to the generation of acid during biodegradation. A leachate liming treatment facility is being constructed on the site. The solids thus generated will be returned to the landfill cells, and the solution will be aerated and evaporated (utilising heat). In this manner, sewer quality effluent should be obtained, which can then be disposed of after analyses have proven that it is of suitable quality.

The Holfontein site has very low permeability and the leachate generated is currently being recycled onto the site. The CSIR is responsible for groundwater monitoring, and Enviroserve monitor carbon dioxide and methane around the perimeter of the site monthly. All rainwater run-off is contained until it has been analysed and the results have been submitted to the Department of Water Affairs and Forestry. Depending on the quality of the run-off, it is disposed of either into the stormwater or sewer systems. Enviroserve have developed their own "Waste-

Safe" programme, which incorporates relevant principles from the ISO and NOSA systems, and the company is also a Responsible Care signatory.

d) Leachability of the jarosite

In 1992, testwork was conducted by Genmin Process Research (currently Billiton Process Research) on the "Composition and stability of the jarosite plant residue produced at Impala Refineries" (Broadhurst, 1992). X-ray diffraction analysis of the residue indicated that the predominant iron species present was haematite, with an approximate haematite/jarosite ratio of 3:1.

It was found that 55% of the Ni and 29.5% of the Co present in the residue could be removed upon washing with acidified water (pH approximately 1.8). The Toxicity Characteristic Leaching Procedure (TCLP) developed by the U.S. Environmental Protection Agency (EPA) was also performed on the residue. The procedure involves leaching by buffered acetic acid solutions (pH 5-6) at 25°C for 20 hours. It was found that the percentages of mobile As and Pb in the residue were low (less than 0.1%), while virtually all of the Se was leached. However, the concentration of all of these elements were far below the EPA regulatory limits (by a factor of more than 10) (Broadhurst, 1992).

The composition of the residue has since changed, with jarosite and not haematite being produced. Enviroserve have recently repeated the TCLP tests on the jarosite residue. This is a pro-active measure which is being performed by Enviroserve on all the solid wastes it receives, in order to verify necessary pre-disposal treatment. The results are given in Table 4.6.

Dr D.A. Baldwin of Environmental and Chemical Consultants evaluated these results. His main concern was the high leachable nickel content, and the fact that the pH of the jarosite was low, and thus would have to be raised prior to disposal. The jarosite is currently pre-treated with lime and ferrous sulphate (due to the possibility of high As content), therefore these factors are being taken into account.

ANALYTE	TCLP EXTRACT (ppm)	ANALYTE	TCLP EXTRACT (ppm)
Ag	<0.005	Fe	0.031
Al	<0.02	Hg	0.004
As	0.001 (EPA 5)	Mn	<0.0001
B	<0.01	Ni	433
Ba	0.0006	Pb	0.163 (EPA 5)
Be	<0.0001	Se	0.002 (EPA 1)
Cd	<0.0003	Sr	<0.0001
Co	3.1	V	<0.003
Cr	0.014	Zn	1.5
Cu	<0.024		
pH of sample	5.6	pH of leachate	4.9

Table 4.6: Jarosite TCLP results.

Note: 100g of sample was extracted with 2ℓ of leachate. The EPA Regulatory limits for some of the elements are given in brackets. According to the EPA guidelines, samples are first pressure filtered, and any filtrate is added to the TCLP extract. The solids are then dried at 100°C to constant mass prior to leaching.

It is evident, however, that the jarosite should be thoroughly washed by Impala prior to disposal, so that entrained nickel is not lost in the jarosite. This is important both from an economic and an environmental point of view.

4.5.6) Effluent:

Details regarding the BMR effluent will be presented in section 4.6.7, and section 4.7.1. The effluent analysis varies considerably from day to day and from month to month, according to the degree of recycling and process control within the BMR. The Ni, Cu, Co, ammonium and sulphate ions present in the effluent were included in the LCI as waterborne contaminants as a worst case scenario (due to possible groundwater contamination during use of the effluent). The average quantities are given in Table 4.7.

COMPONENT	t/MONTH
Ni (waterborne)	5.5
Co (waterborne)	0.44
Cu (waterborne)	0.70
Nitrogenous compounds (waterborne)	137
Sulphates (waterborne)	91
Waste water	25839

Table 4.7: Average effluent composition as entered in the LCI.

4.5.7) Standard flows and other open loop flows:

Nitrogen is vented to the atmosphere after use. The other flows will be discussed under the water balance; section 4.7.1.

4.5.8) Excluded outputs:

Air emissions:

The only stack sampling that is currently performed in the BMR is on the nickel handling dust extraction system. Isokinetic sampling was last done in July 1995. The inlet loading was 7.35gm^{-3} Ni, and the emission was 0.017gm^{-3} Ni, giving a nickel scrubbing efficiency of 99.8% (the error is estimated to be ±0.1%). Vent gases are not monitored, including those from the boilers.

An air quality survey was conducted on Impala's behalf by the CSIR, based on measurements taken over a period of a year (11/94 - 11/95) at a nearby school, in order to determine the health risk of Impala's refining operations to the community adjacent to the Refineries complex. It was found that none of the pollutants measured (SO_2, NO_x, Cl_2 and particulates) exceeded either short (hourly), medium (daily and monthly) or long (annual) term health guidelines (wind direction was taken into account). Thus it was concluded that Impala was not a strong local source of air pollution as at November 1995.

B) STEAM GENERATION OUTPUTS:

The quantity of **ash** produced was calculated from the analytical ash content of the coal (14.4%) giving an average of 779t/mth. This value is somewhat low, as 100% combustion of the combustible material is assumed (the actual quantity is not currently measured). The ash is used by a brickworks, thus it is classified as an open loop output. The gaseous products were similarly calculated from the ultimate coal analysis. The NO_2 output quantity does not include thermal NO_x produced upon the reaction of excess air input with atmospheric nitrogen. The quantity of NO_x produced in this manner depends on the boiler temperature and air mixing, thus the quantity produced cannot be calculated, and should rather be measured (no such measurements were available). In this mass balance, only the oxygen in the input air was included, thus it is consistent to exclude the thermal NO_x produced.

The water in the ash leaving the BMR was calculated based on an average moisture content of 34.5% (as per analysis). The **effluent** derived from boiler blowdowns was estimated to be 750t/mth (it is not measured, but this estimate by process staff should be within 15% of the actual amount). The **steam** generated is supplied to the BMR process (average monthly consumption of 32907t), the hydrogen generation plants (approximately 4600t/mth) and the PMR(1895t/mth on average). The steam loss at the boilers was calculated by difference, giving an average loss of approximately 0.3% of steam produced.

C) HYDROGEN GENERATION OUTPUTS:

The **hydrogen** produced is used by the BMR (on average 72t/mth, primarily for metal reductions), and by the PMR (estimated to be 0.8t/mth). If the demand for hydrogen is low, the back pressure causes excess hydrogen to be **vented** to atmosphere (on average 9t/mth).

The quantity of **carbon dioxide** produced was calculated from the overall reaction (refer to Appendix 2):

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$$

Carbon dioxide is drawn from the MEA circuit primarily for use during the fifth stage neutralisation leach and to purge pipe lines before hydrogen is introduced to them, in order to prevent explosions. It is similarly used in the nickel furnaces and high pressure CO_2 is used to pressurise autoclaves. Excess carbon dioxide is **vented** to the atmosphere. It was assumed that 30% of the CO_2 produced was utilised (a portion of this would also ultimately be vented) and the balance was vented. (Previous investigation into selling this excess carbon dioxide to Fedgas, for use in carbonated beverages, was terminated, as the carbon dioxide was not pure enough).

The **steam loss** at the hydrogen plants was calculated by difference (some of this steam is condensed and recycled to the boilers as condensate returns, but the quantity is not monitored). This quantity was verified as being a valid estimate by BMR personnel.

The **gaseous combustion products** were calculated from the gas composition (refer to Appendix 2 for calculation details). The supplier gave CO_2, H_2O vapour and N_2 as the combustion products.

4.6) WATER MONITORING AND MANAGEMENT

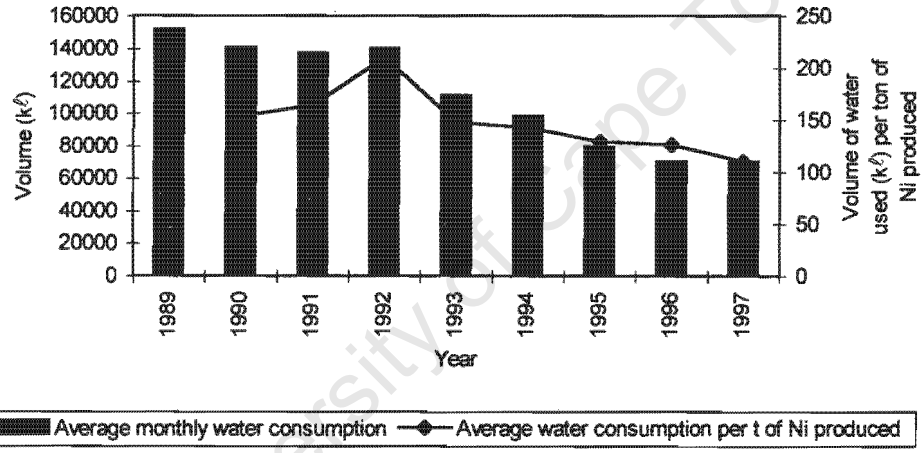
4.6.1) Introduction

This section focuses on water usage and management within the Base Metals Refinery (BMR) of Impala Platinum Refineries Limited. The water management system consists of a number of components, which are inter-related (refer to Chapter 9 for a graphical representation of the overall system (Figure 9.1)). These are: the Rand Water Board input water, which is purchased; the demin and the reverse osmosis plants, which are used to purify water; the boilers, which produce steam from water; the cooling water towers, which are used to cool water; and finally the tailings dam, which serves as an effluent retention pond (for "spent" water). Each water stream is analysed regularly to assess its quality. In addition, water from the adjacent Blesbokspruit watercourse is regularly sampled and analysed, as is ground water which is sampled from a number of boreholes, both in and around the site. This monitoring programme serves to complete the water management system. Each of these components will now be discussed.

4.6.2) Rand Water Board input water

The water management system of the Refineries complex (BMR and PMR) has improved significantly over the past six years or so, due to the introduction of water recycling processes within the plants. Prior to 1995, over 100Mℓ of water was consumed per month by the refineries. By 1996, however, the average monthly water consumption had been reduced to 70.6Mℓ. This improvement is shown graphically in Figure 4.4 below. The ratio of total water used to nickel produced (as obtained from Implats Financial Reports) is included to illustrate that the decrease in water usage was not due to a decrease in production (the BMR uses the majority of the refineries water).

Figure 4.4: Average monthly water consumption and ratio of water consumption to nickel produced at Impala Platinum Ltd Refineries



The average volume of Rand Water Board (RWB) water consumed monthly by the BMR for the period 01/95 to 07/97 was 61Mℓ, with 7.5Mℓ being used for general use in the BMR (toilets, washing, drinking water and so on), and the remainder for demin water production.

Rand Water Board water is sampled daily in the BMR for analysis with a more detailed analysis being performed on weekly samples. Bacteriological monitoring of the water is also performed quarterly. This used to be a mine requirement, as Impala was using its own reservoir to provide drinking water. Today the reservoir water is only used as fire water, but the monitoring is still done on the RWB drinking water. In this manner, the quality of the RWB water is monitored.

4.6.3) Demin plants

Two demin plants utilise cation and anion exchange resins to remove ionic impurities from the water purchased from the Rand Water Board. In each plant, 5.2kℓ of an industrial grade strong acid cation exchange resin is placed in series with a column containing 4.2kℓ of a strong base anion exchange resin above 2.5kℓ of a weak base anion resin. These resins all have styrene divinylbenzene copolymer matrices. The cationic resin has a sulphite functional group, while the weak and strong base anionic resins have tertiary and quaternary amine functional groups, respectively. The resins have an expected life span of 10 years. Spent resin will be disposed of by Enviroserve.

Approximately 55000m^3 of demin water is produced each month, with an average efficiency of 94%. The demin water produced is used as process water (for reagent make-up and so on), as plant seal water (for the autoclaves), as boiler feed water, and as make-up water for the cooling towers. On average (01/1995-07/1997), 6.5kg of solids are removed in total per month by the demin plants (this value is calculated from the difference between the total dissolved solids (TDS) in the RWB water, and the demin water).

The cationic resin is regenerated with sulphuric acid and the anionic resins with sodium hydroxide. On average (01/95 - 07/97), a total of 48 regenerations were performed per month. The effluent thus produced is routed to the tailings pond. After each regeneration, the resins are washed with water to displace residual sulphuric acid or caustic soda. This rinse water is purified for re-use by the reverse osmosis plants, with the final portion of rinse water being used directly as boiler feed water. After approximately 1000 regenerations, a sodium chloride regeneration is done to remove any build-up of ions on the resin beads. A back-wash is also done with water after every 100-120 regenerations, in order to remove resin fines from the columns, which impede water flow. This small quantity of effluent is disposed of in the tailings dam. No topping up of resin has been required to date (after two years of operation).

4.6.4) Reverse osmosis plants

One of two available reverse osmosis (RO) plants currently treats contaminated recycle water (primarily demin rinse water and condensate water), which has a total

dissolved solids content of less than 10000ppm. The effluent is passed through sand filters prior to entering the RO cells, in order to remove suspended solids. Approximately 5000kℓ of water is reprocessed through the RO plants per month.

Flocon 100 is added to the RO circuit, in order to prevent scale build-up, while sodium metabisulphite and EDTA are used to flush the cells and hydrochloric acid is used to clean the membranes. The brine produced by the RO plants is used for washing to some extent, and the remainder is routed to the tailings pond. The permeate is used as feed water to the demin plants, as process water, as plant seal water (for the autoclaves), and as make-up water for the cooling towers. The average recovery of water through the RO plants is 85%.

4.6.5) Boilers

Two boilers are usually in operation at any time. Demin and condensate water are used as boiler feed water, as high quality water is required to prevent corrosion and scale formation which would hinder heat transfer efficiencies and cause damage to the equipment. A coagulant is also added to the feed water to facilitate the settling of suspended solids, which are then removed to the effluent pond during boiler blowdowns. Corrosion and bacterial growth inside the boilers are further prevented by the addition of a chemical mixture called Helamin, which is administered and monitored by an outside company.

The combustion of coal is used to provide heat to vaporise water to steam after the water has been pre-heated via heat exchange with condensate water, seal water and nickel briquette wash water, in order to save energy. On average the boilers supply the plants with 39391t of steam per month. The electrostatic precipitator associated with the boilers has an overall efficiency of 93% with respect to particulate removal (this is according to previous measurements and includes soot blows). The steam generated by the boilers is used for heating in the evaporator units of the BMR, generating vacuum, and for direct and indirect heating in the tanks and autoclaves.

4.6.6) Cooling water

At the BMR, there are two cooling water circuits, which utilise wet or evaporative cooling towers to dissipate heat loads to the atmosphere. The circuit which passes

through cooling tower number 1 has a capacity of approximately 168kℓ. During the period under study, it provided cooling water for the compressors alone (although changes were made during 1998 in order to balance the heat loadings more effectively between the two towers to improve efficiencies and reduce the quantity of make-up water required). The other cooling water circuit has a capacity of approximately 670kℓ. During the period under study it provided cooling water for the BMR process and the hydrogen plants.

Both of the cooling water circuits are treated with a corrosion deposit inhibitor and a microbiocide (Anikem reagents), which are supplied and administered by an outside company. Biocides are necessary because the warm, highly oxygenated water is ideal for biological growth (Noyes, 1993). A larger portion of soot dust blows into cooling tower 1, due to its proximity to the boilers. Cooling water blowdowns are thus required (approximately twice a month). The quantity of blowdown generated is also a function of the quality of the makeup water, the condition of the cooling system, and the amount of water evaporated by the cooling tower. The effluent generated is disposed of in the tailings dam. Similarly, solids removed by side-stream filtration enter the effluent pond.

The main source of water loss from the cooling water system is due to evaporation, with an average water make-up requirement of 11240kℓ/mth to maintain a constant volume. This make-up water is obtained from the demin and RO plants, as well as from condensate water. The monthly volume required depends on the ambient temperature and relative humidity, as these factors affect the rate of evaporation. Cooling tower 2 requires far more make-up water than cooling tower 1, because of the higher operational temperature which results in higher evaporative losses (20-30°C versus 18-24°C in summer, and 10-20°C versus 2-15°C in the winter).

4.6.7) Retention pond

A generalised flow diagram for the effluent circuit is shown in Figure 4.5. Effluent from boiler blowdowns, demin regenerations and RO brine enters the retention pond via one sump, and that from the plant enters via another sump. Rainwater run-off enters the pond directly.

The effluent from the pond passes through bag filters (after lime dosing if necessary) prior to being pumped to an outside company (Ergo) for use in the recovery of slimes dams. The average monthly effluent flow to Ergo for the period 01/95 to 07/97 was 26Mℓ.

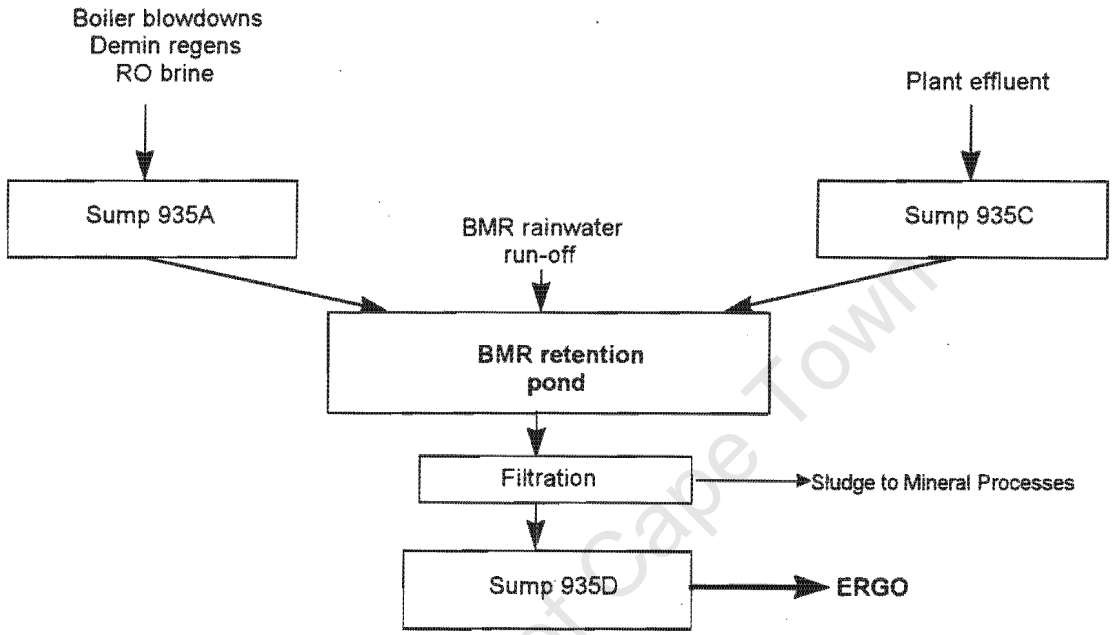


Figure 4.5: BMR effluent flowsheet

Up until approximately two years ago, Ergo required the effluent received to have a pH of seven. The pH of the effluent was frequently below this specification, thus dosage with lime was necessary. This resulted in the build-up of sludge in the pond, containing heavy metals. It was therefore recently desludged, and the solids were returned to Mineral Processes to recover the metal content. The analysis of a composite sample revealed that the sludge contained 1.73% Ni, 0.56% Cu, 0.55% Fe and 522ppm Co. It also contained 301ppm Ir, 80ppm Ag, and <100ppm of Pt, Pd, Au, Rh, and Ru. Ergo has subsequently reduced the minimum pH specification of the effluent to 5.5, thus lime dosage is now seldom required. Desludging is therefore anticipated to be required only every two to three years.

4.6.8) Ground water monitoring

In June 1995, the groundwater monitoring system, which was originally initiated in 1978, was expanded after Wates, Meiring and Barnard Consulting Engineers had

completed a geohydrological survey of the area. It was revealed that the groundwater system consists of a perched aquifer within 6-8m of the surface, which is located in weathered Karoo Supergroup sediments (shale and sandstone). Below this, at a level of 14-20m below the surface, another aquifer is present in a dolomitic layer. The Karoo sediments have low permeability, and therefore semi-confine the underlying dolomitic aquifer, although the Karoo sediments are absent in some areas. The groundwater flows in a north-westerly direction. Due to the proximity of these aquifers to the surface, there is a potential for groundwater contamination. It is for this reason that a short discussion of Impala's groundwater monitoring programme will now be included.

Sampling by the consultants indicated that all water samples were very hard due to natural hardness from the dissolution of calcium and magnesium from the dolomite. High pH values indicated that any contamination was not acidic in nature, and therefore natural weathering of the dolomite had occurred. The heavy metal concentrations were generally low, as expected at high pH values. Elevated levels of aluminium and nitrates occurred in the vicinity of the slimes dam and the PMR. The nitrate contamination could be from sewage disposal or from explosives used when the area was still being actively mined. Aluminium was previously used in the PMR. Overall, the shallow perched aquifer displayed poorer groundwater quality than the deeper dolomitic aquifer.

The groundwater monitoring system involves the sampling and analysis of groundwater from a number of boreholes in and around the Refineries site on a quarterly basis. The positioning of the twelve Impala boreholes are indicated in Figure 4.6. In addition to monitoring at these sites, another borehole located on private residential property near the Refineries site is also chosen randomly each quarter for sampling and analysis. The results are plotted on cumulative graphs, where they are compared to previous results, as well as the running averages. Recommended, maximum permissible and crisis limits, as given by the South African Bureau of Standards (SABS) specifications for water for domestic supplies (1984), are used for comparison purposes, although as the groundwater is not used as drinking water, the validity of the comparison is debatable.

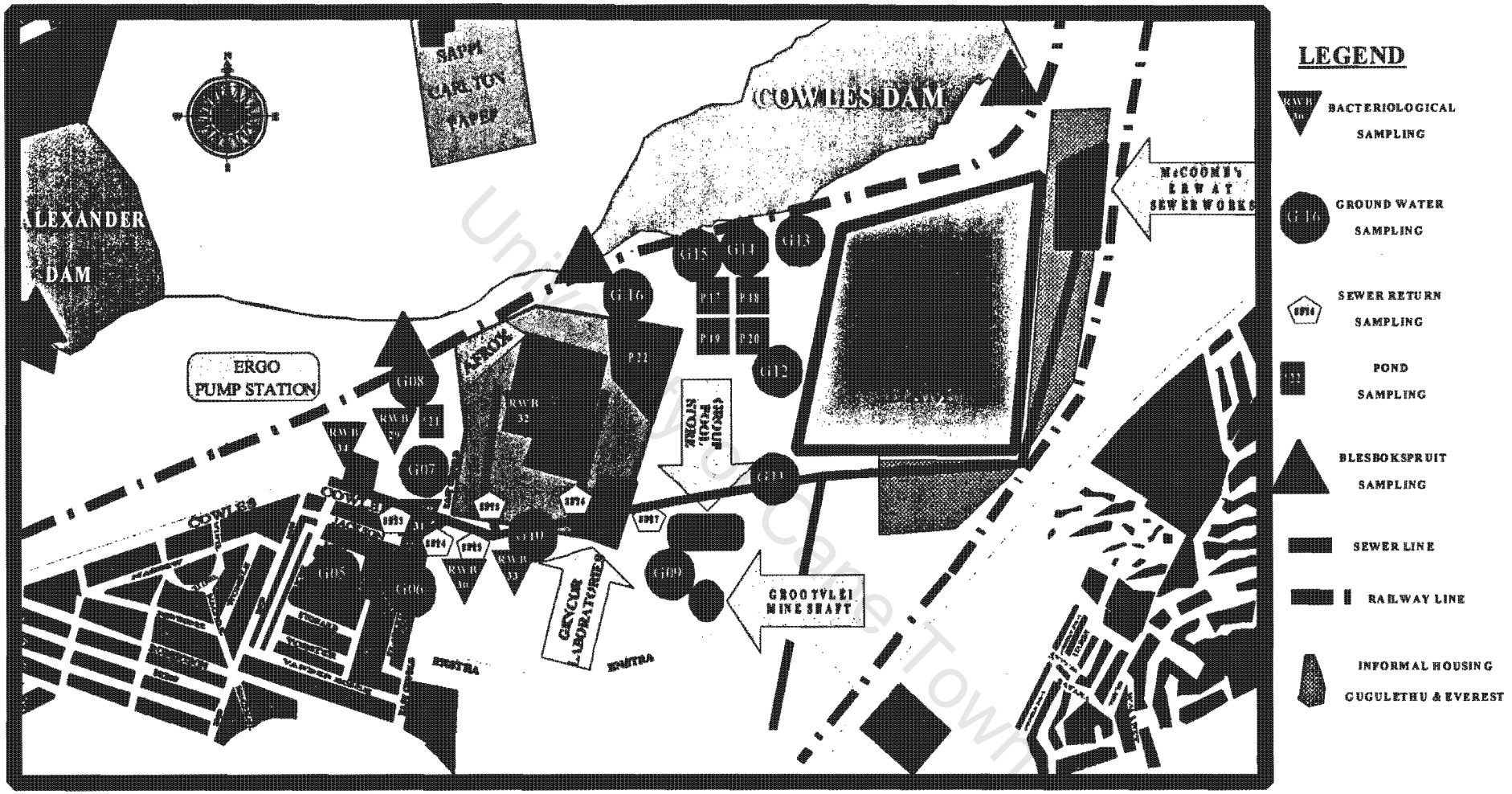


Figure 4.6: Details of Impala Platinum Ltd Refineries water and effluent monitoring programme (Reynolds, 1998).

4.6.9) Surface water monitoring

The Blesbokspruit (a Ramsar site) and Cowles Dam are adjacent to the Impala site, thus surface water sampling is performed quarterly, at four points along this water system, from Alexander Dam upstream, to Cowles Dam downstream (refer to Figure 4.6), although no effluent from Impala enters this water system.

4.6.10) Sewage water

The sewer lines are sampled to ensure that effluent is not disposed of into the public sewer system. Although it is not required by law, this sampling serves to protect the company should there be a query from the downstream sewer works. A pH measurement is done daily, from a grab sample taken downstream of the inlet points, which must be between 6 and 9. Weekly samples are taken at six sampling points, which are composited to form monthly samples for a more detailed analysis.

4.7) MASS BALANCES

4.7.1) Water mass balance

The volume of RWB water which enters the BMR represents the losses to the system. These losses are mainly in the form of effluent which enters the tailings pond; evaporative losses (from the cooling towers); vented steam; and the supply of demin water and steam to the PMR. The jarosite residue also contains 25% moisture on average, and a portion of the RWB water exits the BMR via the sewer system (refer to the monthly water balance in Appendix 2). Other by-products (ammonium sulphate, Se/Te residue and PGM concentrate) also contain a small amount of moisture, although this was not included in the balance as it was not significant.

The quantity of effluent that entered the pond from the various BMR processes was calculated, as a comprehensive metering system is not currently in place. The monthly rainfall figure was multiplied by the BMR and effluent pond surface areas to obtain the volume of rainwater entering the pond. The evaporative losses from the pond surface were also calculated from evaporation measurements taken on site. These values were used in conjunction with the metered effluent flow to Ergo and the measured change in the pond level, to obtain the volume of effluent that entered the pond each month. Thus:

Effluent into pond = Effluent to Ergo + Evaporation + Increase in pond level - Rainfall

The month to month variations in these values were quite large, which were due in part to seasonal fluctuations. Problems with meter operation also lead to errors (such as that for 02/96 as can be seen in Appendix 2). The average overall water balance is given in Table 4.8, again an overall error of 15% is estimated.

STREAM	**SOURCE**	**AVERAGE IN kℓ/mth**
INPUTS		
RWB water	Logsheet	61050
OUTPUTS		
Cooling water make-up	Logsheet	11240
Demin to PMR	Logsheet	910
Steam to PMR	Logsheet	1895
Water to sewer	Logsheet	7548
Moisture in ash	Analysis	410
Moisture in jarosite	Analyses	15
Effluent into pond	As calculated below	13465
H_2O in ash	Calculated	410
Vented steam	Calculated	20703
Inputs-Outputs		4863
% Error		8%
Effluent calculation:		
Effluent to Ergo	Month end report	26073
Evaporation	Month end report	912
Increase in pond level	Month end report	-331
Rainfall	Month end report	13189
Thus effluent into pond		13465

Table 4.8: Average water balance (01/95-07/97).

For some of the earlier months, when the volume of make-up water for cooling tower 1 was not available, an estimate of 10% of the make-up water required for cooling tower 2 was made, based on subsequent measurements. It was assumed that all the water for general use enters the sewer system, except for 20kℓ per day which is used for washing by the Utilities section, and then enters the effluent pond via the stormwater drains. The quantity of steam vented was calculated from the steam loss at the boilers, plus the difference between the steam produced (less the steam to the PMR) and the condensate and seal water returns.

The water balance for the BMR process alone (that is, excluding that relating to the hydrogen and steam generation facilities), is presented in Table 4.9. Water used in the BMR process itself is recycled within the process or leaves the plant with the effluent, jarosite or as vented steam. This quantity of vented steam is not included in Table 4.9, as water added to the process via reagent addition has not been included as an input in this water balance, which would also contribute to vented process steam (the sodium hydroxide is purchased as a 48% solution, for example). It is evident from Table 4.9 that approximately half of the BMR steam input is vented.

STREAM	SOURCE	AVERAGE (IN kℓ)
INPUTS: RWB water	Total less boiler feed & ash water	20391
Steam to BMR	Total prod less H_2 less PMR usage	32907
TOTAL INPUTS		53298
OUTPUTS: Effluent	Total calculated less boiler effluent	12716
Cooling water losses	Logsheet	11240
Demin to PMR	Logsheet	910
Water to sewer	Logsheet	7548
Moisture in jarosite	Analyses	15
Steam vented	Total amount vented less that from H_2 and steam plants	16298
% Steam input vented		50%
TOTAL OUTPUTS		48727
Inputs-Outputs		4571
% Error		9%

Table 4.9: Average water balance for the BMR process itself (01/95-07/97).

4.7.2) BMR unit operation elemental mass balance:

In order to establish an audit trail of environmental impacts back to the processes in which they arise, monthly mass balances, as well as an overall average mass balance, were prepared for the unit operations, as defined in section 4.2. These balances are also a necessary source of information for the environmental assessment of various process options.

The elements included in the mass balances were Ni, Cu, Co, Fe, and S, although the accompanying data files contain results for all of the elements analysed in each stream. This provides a more complete information source, and enables possible future expansion of the mass balances to include additional elements. Ni, Cu and Co were included because they are the primary products of the BMR process, while Fe and S were included due to their potential environmental impacts. The mass balances and the data spreadsheets were verified by the BMR Project Engineering Department. The overall average mass balance is presented in Appendix 3 along with the accompanying average data spreadsheet.

The sources of the analytical results (and flowrates) used in the data spreadsheets are presented in an accompanying data spreadsheet for traceability purposes (refer to Appendix 3). The metal accounting or process control (analysed by a satellite laboratory) stream number is noted. Other sources of data such as month end and performance reports or process logsheets are given. The average analyses of four spot samples, which were taken over a period of time from each stream which was not routinely analysed, are included. The analytical units of each component in the streams are also given. Month-to-month analytical variation in process streams occurred due to the dynamic operation of the plant with respect to inputs (with higher %RSDs generally being evident for the minor constituents in streams).

Real flowrates were used when available (this included the matte, toll refining, and reagent inputs, and the product and by-product outputs). The inter-unit flows were derived from those used in the Metsim computer simulation model of the BMR process. This is a steady state model, which uses the feed material composition into the BMR process as a basis. The chemical reactions occurring in each unit operation are assumed, as are the conversion, temperature and concentration controllers in the model. These are all based on plant experience (McDowell and Spandiel, 1996).

The inter-unit flow values from Metsim were adjusted according to the ratio of the nickel input from matte each month, in comparison to that used in the Metsim model, as the addition of matte is the start of the process (and thus the quantity of matte milled effects all subsequent flowrates). In addition, nickel is the primary input to the process thus the flowrates would be expected to change in a similar manner to the nickel input in the matte.

These nickel input ratios ranged from 0.27 during months of poor matte supply due to problems at Mineral Processes, to 1.26. The months of poor matte deliveries were included in the averages, because the large number of months considered diluted their effect, and very similar results were thus obtained whether they were excluded or included. During these months of poor production, the decrease in metal lock-up in the process, as gauged by metal accounting calculations, were included in the mass balances.

The adjusted flowrates (estimated error of 10%) were used in the conversion of the analytical results to mass flowrates (in kg/hr) for use in the unit operation mass balance. Flowrate ratios indicating the division of reagent usage between the different units were calculated from the Metsim model (as shown at the bottom of the data spreadsheet in Appendix 3). These were then applied to the actual total monthly reagent consumptions to derive reagent flowrates per unit operation, as the actual flowrates were unavailable. The ratio of the matte input quantities to the two first stage leach plants (which operate in series) were applied to the analyses of the solids exiting each leach in order to obtain a combined analysis for these streams.

The balance closures for the individual unit operations were poor in some cases, due to a combination of analytical deficiencies (not all elements included in the balance were analysed in each stream), analytical errors (especially for those streams analysed for process control purposes in satellite laboratories in the plant) and the uncertainties in the flowrates. Mass balances based on monthly averages are suitable for metal accounting purposes, however. The overall balance (in terms of considering all of the unit operations) had more acceptable errors for each element considered. These errors for the overall average balance ((inputs-outputs)/inputs) were: -7% for Ni; 3% for Cu; -6% for Co; -13% for Fe; and 18.5%

for S. The percentage errors were based on the total metal inputs from matte and toll refining material, while that for sulphur included all inputs.

The negative balance for Fe has been attributed in part to the dissolution of Fe-containing process equipment and mill balls. As sulphur is not analysed in many of the inter-unit streams, an overall sulphur balance was done in terms of inputs and outputs to the process. The relatively large error in the sulphur balance could be due to analytical inaccuracies, although the majority (25 out of 31 months) of the monthly sulphur mass balances were positive. This indicates that the exclusion of air emissions (SO_2 which is vented from the process (such as from the nickel reduction vents), and sulphuric acid mists which are produced in the copper electrowinning section) contributed to the error.

The electricity information available for the unit operations was given in section 4.4. Water consumption by individual sections of the BMR is not presently monitored, thus data relating to actual water usage within the various unit operations, as defined in the process flow diagram, is not available. The Metsim process model calculates the process water consumption of each unit operation, based on projected densities of incoming streams and required pulp densities. It does not incorporate recycling of water within sections, such as wash water which is reused to adjust the pulp density of streams, thus the actual ratio of water usages between unit operations may differ based on the extent of water recycling within the individual sections. It was assumed as a first approximation, however, that the extent of recycling within each unit operation was similar.

The Metsim water consumptions, based on typical BMR inputs, were therefore used to calculate ratios of water usage by the various unit operations. These ratios were then used to allocate water consumptions to each unit operation, based on the actual monthly process water consumption as recorded on process logsheets (average of 7636kℓ/mth). The results are given in Table 4.10.

UNIT OPERATION	WATER CONSUMPTION kg/h	% OF TOTAL CONSUMPTION
Comminution	225	2.1
1st stage & Cu cementation	332	3.1
Jarosite	1161	11
Ni purifn & redn	3518	33
MDS	0	0
Co purifn & redn	228	2.1
Amm sulphate	0	0
2nd stage	4570	43
3rd stage	209	2.0
4th stage	142	1.3
5th stage	48	0.5
Cu purifn	56	0.5
Cu winning	116	1.1
TOTAL	**10605**	**100**

Table 4.10: Relative water consumptions of the BMR unit operations, based on average monthly process water usage.

As can be seen from Table 4.10, 2nd stage leach consumes the most water of all the unit operations (43%), primarily for pulp density adjustments. The other major usage occurs in the Ni purification and reduction circuits (33%), while 11% of the total water consumed is used in the jarosite section (mainly for washing purposes). The other ten unit operations consume the balance of the water used by the process per month.

The life cycle inventory data presented in this chapter in terms of inputs and outputs will now be linked to the environmental impacts associated with them during the classification step of the LCA.

Chapter 5: IMPACT ASSESSMENT

5.1) INTRODUCTION

In a LCA, the information presented in the LCI is related to specified environmental concerns during the classification stage. Contributions of individual substances to each problem are aggregated to form environmental profiles relating to the process as a whole, which can then be evaluated. Each of these steps will now be presented with respect to the LCI information of Impala Platinum's Base Metal Refinery (as given in Chapter 4).

5.2) SOFTWARE USAGE

The Pira Environmental Management System (PEMS) is a software package designed for conducting life cycle assessments, providing for transparency of methodology and data use. PEMS version 4 has four main databases, containing environmental data on materials manufacture, transportation, energy generation and waste management, as noted in section 3.3.2. PEMS is thus used to incorporate the LCIs of reagents and energy used (and possibly wastes generated) by the process studied, into the LCA related to it. Much of the data is derived from studies conducted in the plastics and packaging industries, thus some reagents which are commonly used in the base metal refining industry are not included in the database, such as sulphur dioxide. This problem is common to the majority of commercial LCA software packages which are currently available.

The databases also contain information on a variety of environmental effects such as the depletion of non-renewable resources, acidification, and greenhouse warming potential, which are used in the classification process. There are a number of limitations relating to these, however, which will be discussed in section 5.3. PEMS allows for the valuation of classification results into an overall score, if this is desired, and sensitivity analyses may be conducted, in order to assess the effect of data uncertainties on the results (refer to Chapter 6).

5.3) CLASSIFICATION

5.3.1) The classification process

Human interventions in the environment (such as emissions) may have effects which result in environmental problems (such as acidification). Classification

involves labelling inputs and outputs according to the effect categories they contribute to, which is followed by characterisation to weight and aggregate the inputs and outputs to determine scores for the categories (Heijungs, 1992a). An environmental profile, which is a list of all the environmental effects in which a product plays a part, is thus produced. This is known as the problem-oriented approach. A number of these problems are the topics of international debate, and thus form the focus of related international conventions and protocols, such as the Montreal Protocol of 1990, which deals with the depletion of the ozone layer.

Four steps can then be distinguished in the classification process:

1. The environmental problem types are defined.
2. Classification factors are defined, which indicate the contribution of each input and output listed in the LCI to the problems defined in 1 above, in relation to a reference compound.
3. The environmental inputs and outputs are multiplied by the classification factors as given in 2 above. The results pertaining to each problem category are then aggregated into effect scores.

It must be noted that classification and characterisation are not purely technical processes, as a number of subjective and value choices are made, involving the grouping of effects into impact categories and in generating classification factors for each category (Barnthouse, 1998), which will be elaborated on in section 5.3.4. The classification factors used in the PEMS software are derived from those given in Heijungs (1992a), with the exception of the resource depletion (for which the global recoverable reserves are used), and the greenhouse effect impact categories. Updated "provisional best estimates" from the Intergovernmental Panel on Climate Change (1995) is used in the determination of global warming potentials (Pira, 1998).

5.3.2) Categories of environmental problems

Three categories of environmental problems, which are based on environmental mechanisms, have been defined, as follows in Table 5.1 (Heijungs, 1992b). Which of these problem types are included in a LCA study are dependent in part on the availability of inventory data and classification factors.

The environmental problems pertinent to this study will be discussed in more detail in section 5.3.3. With respect to the three categories given in Table 5.1, depletion of resources is based on available resources and the rate of extraction and use of them. The completeness and accuracy of data in these respects may thus be limited (Guinée, *et al*, 1993a). Damage to the environment results from changes in the structure of the environment, as shown in Table 5.1 above, while pollution occurs due to the emission of potentially harmful substances.

Depletion		Pollution		Damage
Abiotic resources		Greenhouse effect		Drying out
Biotic resources		Depletion of the ozone layer		Physical ecosystem degradation
		Human toxicity		Damage to landscape
		Ecotoxicity		Direct/indirect human victims
		Photochemical oxidant formation		
		Acidification		
		Eutrophication		
		Radiation		
		Waste heat		
		Noise		
		Odour		
		Working conditions (Occupational Health)		

Table 5.1: Categories of generally recognised environmental problems (Heijungs, 1992b).

It should be noted that environmental problems result in an effect chain, which will be discussed with reference to global warming as an example. Global warming is caused by the emission of certain substances (such as carbon dioxide), which absorb infra-red radiation. This perturbs the balance between energy absorbed by the earth's atmosphere and that which is reflected. The perturbation is known as the "greenhouse effect", and is the primary effect in the effect chain. The change in global temperature which would result is a secondary effect. Subsequently, this change in temperature could cause the sea level to rise due to expansion of the water mass and due to melting of the ice caps (a tertiary effect). Ecosystems could also be negatively affected, and a host of other higher-order effects could result (Guinée, *et al*, 1993a). The ease of predicting these effects, and the accuracy of the predictions, decreases as the order of the effect increases. It is therefore best

to link the inputs and outputs with the lowest order effect, which in the example above is the greenhouse effect.

There are a number of limitations with the current classification process:

- All potential effects of an emission with parallel impacts are quantified according to the total quantity released during the LCA classification process. An emission of 2kg of SO_2, for example, would be attributed in full to both acidification and human toxicity, which is not physically possible. (Although this is not a problem for direct serial effects such as a molecule of NO_x contributing to both acidification and nutrification). Developments in environmental impact modelling to include the fate of emissions will eliminate this double accounting (Guinée *et al*, 1996, and 1998).

- A site-specific approach to environmental problems is not generally feasible, due to the quantity and quality of data required. Thus the generic classification used in current LCA methodology would, for example, classify emissions of both nitrogen and phosphate to the problem of nutrification but it is only the nutrient that is locally deficient that can actually cause the effect. The possible regionalisation of LCA to include the sensitivity of the area to emissions is currently under discussion (Guinée, 1998). The Precautionary Principle (Jackson, 1993) or worst case scenario is, however, currently employed.

- Synergistic impacts are not currently included in LCA classification. These may occur when the impacts caused by a combination of two or more types of emission are larger than the sum of the individual impacts.

The limitations in the classification methodology will be discussed in more detail in section 5.3.4.

The relationship between environmental protection areas (resources, human health and ecosystem health) and the impact categories are shown in Table 5.2. Specific impact categories may thus be selected, based on the specific endpoints which represent what the study desires to protect or focus on, such as smog formation or the greenhouse effect. Those categories chosen should be independent to prevent overlap and double accounting, but should cover all relevant problem areas. The impact categories should also be based on environmental mechanisms which are

supported by scientific evidence and the total number of categories considered should not be too large, in view of the fact that a decision-making process will follow (Barnthouse, 1998).

Impact category	Resources	Human health	Ecosystem health
Depletion			
Abiotic resources	+		
Biotic resources	+		
Pollution			
Greenhouse effect		(+)	+
Ozone depletion		(+)	(+)
Human toxicity		+	
Ecotoxicity		(+)	+
Photochemical oxidant formation		+	+
Acidification		(+)	+
Nutrification			+
Damage			
Land use			+

Table 5.2: Integration of protection areas and impact categories (Guinée, 1994).
Where + refers to a direct potential impact and (+) refers to an indirect potential impact.

5.3.3) The contribution of base metal refining to environmental problems

The main environmental impacts arising from the nickel industry are associated with air pollution and heavy metal leachate problems from sludges and solid waste (UNEP IE/PAC, 1993). The air emissions are largely due to dust, particulate, and sulphur dioxide emissions. Hydrogen sulphide and ammonia, associated with the leach process, and combustion gases may also be constituents of atmospheric emissions. As noted in section 4.5, it is only the combustion and hydrogen plant product gases, together with water vapour losses and vented nitrogen which are included in the LCI with respect to air emissions.

A number of environmental problems will now be introduced, including specific reference to contributions to these problems by the base metal refining process itself.

A) Depletion of resources

The depletion of resources is concerned with sustainability. If reserves decline or if consumption exceeds replacement rate, depletion may become a problem. This

may lead to the extraction of poorer or less favourably sited resources, leading to greater emissions and environmental damage. The use of coal and Sasol gas by the BMR operation are examples of resource depletion. The effect scores are obtained from the ratio of resource use to reserves.

B) Acidification

A number of acidifying substances (NO_x, SO_2, $HC\ell$, HF and NH_3) may be emitted to the air by industrial processes. The chemical equations of those of relevance to the BMR operations are (Heijungs, 1992b):

$$NO + O_3 + \tfrac{1}{2} H_2O \rightarrow H^+ + NO_3^- + \tfrac{3}{4} O_2$$

$$NO_2 + \tfrac{1}{4} O_2 + \tfrac{1}{2} H_2O \rightarrow H^+ + NO_3^-$$

$$SO_2 + H_2O + O_3 \rightarrow 2H^+ + SO_4^{2-} + O_2$$

$$HC\ell \rightarrow H^+ + C\ell^-$$

$$NH_3 + 2O_2 \rightarrow H^+ + NO_3^- + H_2O$$

Acidification classification factors (acidification potentials) are derived from the propensity of a substance to release protons, as compared to SO_2.

Several environmental problems are associated with acid rain, which is a consequence of these acidification reactions. These include leaching of nutrients from soils and fish mortalities in acidified waters. Emissions by low level (in terms of height) sources affect the local urban area whilst high level sources disperse emissions over a much larger area. SO_2 and other pollutants emitted at high levels may be transported over very large distances by the atmosphere, during which reaction to sulphuric acid may occur, leading to acid rain problems at great downwind distances. This problem is most acute in Scandinavia, which itself emits relatively little SO_2 (Harrison, 1990).

The process of acidification may be reversed by liming, in order to maintain normal plant and animal ecosystems. This is very expensive, however. In West Germany alone, it was estimated that the liming of soils and waters to halt the progress of acidification would cost £15 000 million, as of 1990 (Harrison, 1990). Clearly emission control at source is the more feasible alternative.

C) Photochemical smog

Photochemical oxidant formation (most importantly ozone) in the troposphere is a result of the reaction of NO_x with volatile organic compounds (VOC) in the presence of ultra violet light. This causes summer smog, which may have negative effects on people, plants and crops (Heijungs, 1992b). Smog also increases the reflectivity of sunlight and thus may cool the earth slightly (the opposite effect to that of greenhouse gases) (Ayres, 1996). Photochemical ozone creation potentials are defined as the ratio of the change in ozone concentration due to the emission of a VOC to that due to the emission of ethylene. PEMS utilises this definition and the kg of NO_x generated is given as an additional impact category, due to the interdependency of VOCs and NO_x in the generation of photochemical smog (Pira, 1998). NO_x produced during the combustion processes of the BMR would contribute to photochemical smog formation.

D) Eutrophication

The enrichment of water sources by plant nutrients (eutrophication or nutrification), has been named as one of the key pollution issues in South Africa (Department of Environmental Affairs and Tourism and Department of Water Affairs and Forestry, 1997). Eutrophication may lead to the disturbance of ecosystems due to the excessive growth of one species (such as algae), or due to changes in the physical characteristics of the water (such as the degree of light penetration) or its chemistry (lower oxygen levels or higher pH). Algae at high densities may also produce toxins which kill fish.

Nitrogen and phosphorus are the two nutrients most implicated in eutrophication. Growth is normally limited by phosphorus rather than nitrogen, due to the fact that phosphorus is less soluble. Consequently it is often an increase in phosphorus concentration which stimulates excessive plant growth in fresh waters (Harrison, 1990). The eutrophication potentials are based on phosphate as a reference compound, and relate to an increase in biomass. The nitrogenous air emissions produced by the BMR operations could enter aquatic systems upon rain wash-out. The nitrogen content of the effluent could also result in a eutrophication effect.

E) Ozone depletion

Ozone in the stratosphere absorbs biologically harmful ultraviolet radiation, thus the depletion of this ozone layer has potentially adverse effects on human health and on aquatic and terrestrial ecosystems. Data indicates that the release of chlorofluorocarbons is primarily responsible for ozone depletion, thus the use of these compounds (primarily in refrigeration) is being rapidly phased out (Harrison, 1990). CFC-11 is used as a reference compound in the establishment of ozone depletion potentials. As the BMR process does not use or generate CFCs directly, the contribution of the process to the problem of ozone depletion is expected to be small (due to use or emissions by reagent suppliers only).

F) Water usage

In South Africa there is a problem with respect to the country's water balance, as "there is a significant maldistribution of demand and supply - in short - the demands are where the supply is not, and vice versa". Demand is greatest in the interior of the country, while "untapped resources are concentrated along the coast" (Middleton, 1998). It is for this reason that water usage was included as an impact category.

The major users of water in South Africa, and their annual water consumptions are given in Table 5.3. Demands are estimated to increase to 20 000 million m^3 per annum by the year 2010 (Middleton, 1998).

Although it is evident that the agricultural sector is by far the largest consumer of water, industry also contributes to 7% of the consumption. In view of these factors and the geographical location of Impala's BMR, the significance of water usage by the operation should not be disregarded, thus it is included as an impact category. It is also an area where cost savings can be made.

DIRECT USE	MILLION m^3 PER ANNUM	PERCENTAGE (%)
Agriculture (irrigation)	9 700	51
Agriculture (stockwatering)	290	1.5
Nature conservation	180	1
Power generation	450	2
Industry	1 400	7
Mining	500	3
Municipal and domestic	2 300	12
Indirect use:		
Forestry	1 400	7
Ecology	2 800	15
TOTAL	19 020	100

Table 5.3: Major users of water in South Africa, with usages as of 1990 (Middleton, 1998).

G) Salinisation

An increase in the concentration of dissolved inorganic compounds in water leads to salinisation, which has been listed as another key pollution area in South Africa (Department of Environmental Affairs and Tourism and Department of Water Affairs and Forestry, 1997). Discharge of municipal and industrial effluents, irrigation return water, and seepage from waste disposal sites are some of the anthropogenic sources of increased salinity.

There is not much information available as to the impacts of increased salinity on aquatic ecosystems, although effects on users of the water are well known, such as the increased need for pre-treatment of boiler feed water, increased scaling of industrial equipment, and a reduction in crop yields. Salinisation is not included as an impact category at this stage, although current potential salinisation impacts associated with effluent disposal to Ergo should be noted. This will be discussed further in Chapter 9.

H) Toxicity

a) Introduction

"Toxicology is the study of potential poisons and is concerned with the harmful effects of xenotoxic agents (i.e. agents from outside a living organism) on biological systems" (Conard, 1997). When dealing with this topic, one must remember that all materials are toxic, dependent on the dose level.

There are various properties of substances which determine their ability to react with biological systems. These include solubility (in water and biological fluids), reactivity, photosensitivity, molecular or ionic size, electronegativity and oxidation state. Thus speciation in terms of the chemical and physical states of substances is important in toxicology. There are also many factors which affect absorption, once exposure to a substance occurs. These include duration of exposure, temperature, health of the exposed organism and so on. Organisms are capable of dealing with certain amounts of toxins, thus there exist thresholds below which no toxic response is evident.

"The definition of appropriate classification factors for human toxicity and ecotoxicity is one of the main methodological bottlenecks of the classification" (Guinée, *et al*, 1993a). Consequently, much research is currently being done on human and eco-toxicities. The problem of developing classification factors for human toxicity and ecotoxicity arises primarily from the variations in mechanisms of these effects, as well as a lack of scientific evidence and data for many compounds. The current adding of effects regardless of mechanisms or action of the toxin or the target organs affected is contrary to toxicological fundamentals. It has been suggested (Owens, 1997b) that the human toxicity classifications in LCA could be improved by having a number of "subscores" for different categories of effects (for example, carcinogens, organ toxins, and so on). Alternatively, categorisation based on persistence could be used, although other factors such as bioaccumulation and biomagnification should also be considered. It is not feasible to have a large number of impact categories, however, as this would complicate the decision making process to follow.

Various limits and guidelines, determined by the World Health Organisation (WHO) and the Dutch National Institute for Public Health and Environmental Protection (RIVM), are currently used by such LCA software programmes as PEMS, in the calculation of no-effect levels (for example, acceptable daily intake (ADI) and tolerable daily intake (TDI) values are used as no-effect values for human toxicity and no effect concentrations (NEC) for ecotoxicity). Emissions are compared to these to calculate effect scores (Guinée and Heijungs, 1993c).

The importance of spatial differentiation to toxicity is evident in the example of solvent emissions into outdoor air as opposed to indoor air, as current LCA classification methods would indicate the same potential human health effects in both cases. Characteristics of the source type (height, strength, and temporal pattern), as well as the characteristics of the receiving environment (surface and population density of the exposed area), ideally need to be considered (Vigon, 1997d).

Multi-media environmental models (such as the Mackay models) assume that the relationship between the flux of a substance and the toxic effect is linear (Guinée and Heijungs, 1993c), which may not always be the case. An exposure modelling constant is incorporated, to take into account the lifetime of a substance, as well as partitioning coefficients (between media) and exposure routes. For the calculation of human toxicity classification factors, for example, a distinction is made between respiratory and oral exposures, which are then added to obtain a total toxic effect (uptake through the skin is not presently included in the standard Mackay model) (Guinée and Heijungs, 1993c). High exposure levels, resulting in acute toxicities are not considered, thus these models are limited to chronic effects. Secondary indirect human exposure routes are also excluded (such as exposure by the consumption of food products which were produced with polluted sludge or manure), which may not be justified for persistent substances such as heavy metals and pesticides.

A number of computer models are being developed (such as the Uniform System for the Evaluation of Substances (USES) developed by RIVM for the Dutch government) (Guinée et al, 1996), which incorporate persistence and other effects into the determination of classification factors. Data for these effects is rather limited, however, thus default values are often used, which incurs errors. In

addition, the majority of chemicals included in the USES database, for example, are organic (of the 94 chemicals, 10 are metals and 3 are inorganic compounds) (Guinée et al, 1996).

Due to the fact that the BMR effluent is currently pumped to Ergo for use in slimes dam recovery, it is possible that impurities in it may percolate to the groundwater, and thereby have an impact on aquatic ecosystems. A number of the reagents used in the process and the jarosite generated, have potential toxic effects. Human and eco-toxicity will now be discussed with specific reference to metals.

b) Ecotoxicity

For ecotoxicities, terrestrial and aquatic ecosystems are distinguished because of the different species present and the different exposure routes. Extrapolation from single species toxicity data is currently employed for ecotoxicity, which has obvious limitations, as even rats and mice do not always respond in the same manner to a substance (such as butadiene) (Watson and Golding, 1998). Lethal concentrations for 50% of the organisms (LC_{50}), the effect concentrations for 50% of the organisms (EC_{50}), and the no observed effect concentrations (NOEC) are used in the derivation of no (adverse) effect levels (NEC) or maximum tolerable concentrations (MTC). Conservative extrapolation factors are used so that it can be assumed that 95% of all species of the ecosystem will be protected by the no effect levels (Guinée and Heijungs, 1993c). The PEMS software uses classification factors for aquatic and terrestrial ecotoxicity based on these MTC values, as derived in Heijungs (1992b) from Environmental Protection Agency (EPA) data. Exposure factors are excluded, due to a lack of data on partitioning, degradation and immobilisation processes.

EPA data is taken from both standardised tests used for regulatory compliance, such as the aquatic ecotoxicity testing of algae, daphnia and fish species. When a substance falls outside US regulatory testing requirements (such as in the case of metals), data is taken from scientific literature where testing has been done on any number of other organisms. The most sensitive "indicator" species (those with the lowest NOEC, LC_{50}, and EC_{50} values) from scientifically valid studies are then used by the EPA (Reagan, 1999, and US EPA, 1996).

A number of factors affect the toxicity of metals. The bioavailability of metals, for example, affects bioaccumulation by organisms, as essential elements or

micronutrients (such as copper) are accumulated if the availability is low, thus toxicity can occur at a deficiency. Studies have been undertaken to determine the reaction kinetics of nickel metal and nickel oxide with aqueous media, in order to determine bioavailability under aquatic environmental conditions. It was found that the available surface area, as well as the physical-chemical preparation of the metal influenced the metal transformation characteristics (Skeaff and King, 1998). Metals are persistent in the environment (they do not biodegrade) but biomagnification of most metals up the food chain does not occur (biomagnification is important for those metals which can be alkylated such as mercury and tin, Conard, 1997).

A detailed environmental risk assessment for nickel in the European Union was performed based on the European System for the Evaluation of Substances (EUSES) (Technology Sciences Group Incorporated, 1998). This study included the effects on toxicity of partitioning, degradation, bioaccumulation, and so on. However the major limitations were given as a lack of data and information, which made it difficult to draw conclusions from the study.

The toxicity of heavy metals to aquatic ecosystems also depends on its speciation as simple ionic and lipid soluble forms of metals are most toxic. Copper ions, for example, are toxic, whereas copper bound to organic matter is not. Then again, complexation to organic matter is highly dependent on pH, because at low pHs, hydrogen ions saturate the available bonding sites on the organics, while at high pHs, free metal ions are not the prevalent metal species in solution. Increased hardness of the water decreases copper uptake in fish (and thus decreases toxicity), as the calcium ions present saturate the gill receptor sites which transport the ions from the bulk water to the bloodstream. In soils, the partitioning of a metal between soil and soil solution is a primary determinant of the toxicity risk that a given concentration of metal poses (Allen, 1996), as the solid phase concentration does not reflect mobility or bioavailability.

c) Human toxicity

Chemical toxicity may be measured by *in-vitro* studies, which involve experimenting on tissue independent of the whole organism, thus the inherent disadvantage is that the response of the whole organism is unknown. Alternatively, *in vivo* studies may be performed on whole living animals. Human populations are studied via epidemiology, for example, which is the study of the distribution of disease

frequencies in human populations. Extrapolations from these studies are made, in most cases, in the direction of being overprotective of humans to safeguard against uncertainties in the extrapolation process (Conard, 1997).

In order to ascertain risks in exposed humans, the exposure dose needs to be related to a blood dose, a target dose (the amount which reaches the organ where the compound has its effect), and to the relative toxic potency of the compound, as compared to a reference chemical. Ideally, structure-activity relationships (molecular size, shape, polarity etc), pharmacokinetic studies (absorption, metabolism and distribution) and mechanistic studies (intracellular reactions) should be taken into account when determining human toxicities (Watson and Golding, 1998).

Animal and human health studies have shown that some compounds of nickel cause adverse health effects, although the majority of nickel compounds including the metallic form and alloys do not appear to do so, although contradictory toxicity data from different studies have resulted in inconclusive knowledge about the carcinogenicity of some nickel compounds (such as soluble nickel like nickel sulphate hexahydrate (NiPERA, 1998)). There has been a tendency by regulators, however, to assign the same toxicity to all nickel compounds (Curcio, 1998).

"Nickel metal and nickel soluble salts are potent skin sensitizers, which can lead to allergic contact dermatitis" (inflammation of the skin), although such dermatitis is not evident in the nickel industry, which suggests that tolerance may develop (Conard, 1997). Soluble nickel compounds are more toxic than those which are insoluble with respect to ingestion exposure routes, although the solubility in the acidic gastric fluids must be taken into account. Nickel absorption from drinking water is highly dependent on the presence of food in the stomach, and it has been observed that no chronic effects are evident upon exposure of this kind. In terms of inhalation, there is evidence which suggests that soluble nickel compounds may enhance respiratory carcinogenicity. Historically, inhalation exposure to very high concentrations of nickel compounds in the nickel producing industry has been associated with an increase in the incidence of respiratory cancers (such as lung and nasal tumors) (NiPERA, 1998). Toxicological effects following this type of exposure are often due to synergistic mechanisms resulting from co-exposure to arsenic and copper, for example.

In terms of chronic effects, studies on occupational respiratory exposure (such as the "Doll Study", named after the epidemiologist, Sir Richard Doll, who chaired the International Committee on Nickel Carcinogenesis in Man), indicated that sulphidic nickel (principally Ni_3S_2) was associated with lung and nasal cancers. Similar results were noted for green nickel oxide, although the results were not conclusive because exposures were mixed, as copper was also present. Metallic nickel was not viewed as a respiratory cancer hazard. These results were later confirmed by animal studies (Conard, 1997).

Particles of the size range 2-6μm are most readily transported into cells where the presence of low pH and enzymes may facilitate Ni^{2+} ion release. The vesicles, which serve as transport vehicles, appear to fuse with the nuclear membrane, and in this manner, Ni^{2+} may be delivered to DNA regions, with subsequent carcinogenic potential (Oller, 1998a).

The European Union has indicated their intention to classify all alloys containing more than 1% of nickel as Category 3 carcinogens (possible risk of irreversible effects) according to the Council Directive 88/379/EEC on the approximation of laws, regulations, and administrative provisions relating to the classification, packaging and labelling of dangerous preparations (Cutler, 1997) (America has not adopted this standpoint as yet). "This includes nickel-containing stainless steels - a potentially damaging situation for the nickel industry. This approach takes no account of either the considerable differences between an alloy and a simple mixture of its constituents or the decades of experience of producing and fabricating stainless steel without any documentary evidence of carcinogenicity" (Cutler, 1997). The metals industry is consequently very active in reversing this position, by initiating studies via the Nickel Producers' Environmental Research Association (NiPERA), for example.

At the 1998 Annual General Meeting of NiPERA, the Cobalt Development Institute (CDI) requested assistance from NiPERA, with respect to toxicity studies on **cobalt**. The NTP (US National Toxicology Programme) animal inhalation study of cobalt sulphate heptahydrate was positive for respiratory and adrenal tumours (both benign and malignant) in male and female rats and mice. Based on this, cobalt sulphate will be given a Category 2 classification (a suspected human carcinogen).

The potential negative impacts of the results of this study on the cobalt market is cause for concern for cobalt producers, as this classification may be extended by regulators to other cobalt compounds, such as the metal or cobalt oxide (Oller, 1998b). The relevance of relating the results of animal studies to humans also needs to be investigated, as mechanistic variations could be present, as has been noted with respect to nickel (Oller, 1998c). Fine Co powders and soluble salts, such as the sulphate, are also toxic to aquatic organisms and may have long term effects on aquatic environments, as Co affects the growth rate of algae (Yawili, 1996).

Copper is essential to human health, as it is required for enzyme production, for example. Acute copper poisoning is rare, as ingestion of copper salts generally induces vomiting. Chronic copper poisoning is also very rare, as healthy human livers are capable of excreting considerable quantities of copper. Thus the few reported cases of chronic copper poisoning relate to patients with liver disease (Copper Development Association, 1998).

Upon consideration of the limitations with respect to the current LCA toxicity classification methodology, the toxicity impact category results should be viewed with caution. The PEMS software uses the human toxicity classification factors (for air and water emissions) derived in Heijungs (1992b). The exposure factors of which incorporate dispersion effects derived from Mackay models, while partitioning, degradation and immobilisation are excluded. The effect factors are based on ADI, TDI and air quality guidelines (AQG). Uncertainty factors are applied in the calculation of these values (which may be as high as 1000 or more depending on the volume and quality of the data available (Heijungs, 1992b)). For both human and eco-toxicities, the classification factors should therefore be considered to be preliminary. Developments in the determination of ecotoxicity and human toxicity classification factors for emitted substances are thus focusing on the inclusion of intermedia transport and fate parameters (Guinée *et al*, 1996, and 1998).

l) The greenhouse effect

This environmental problem was explained in section 5.3.2. Carbon dioxide is the reference compound used in the classification process to derive global warming potentials (GWPs) for other compounds. Carbon dioxide produced during the combustion processes in the BMR, as well as that released in the production of

reagents and the generation of electricity, would thus contribute to this impact category.

5.3.4) Limitations in the current LCA classification methodology

The discussion in section 5.3.3 indicated that there are currently limitations in the classification process, which will now be consolidated. It has been noted that "an assessment of an entire system, a network of industrial operations over its product life cycle, is difficult. It is even more difficult as one then attempts to relate the elaborate system to a diverse range of even more complex environmental issues" (Vigon, 1998c).

The current classification process assumes that no **thresholds** exist. There are critical loads or thresholds, however, below which the risk of adverse effects is reduced. Thus a critical load is an indicator for sustainability of an ecosystem. By measuring physical and chemical properties of an ecosystem, sensitivity to acidification, for example, can be given as a "critical load of acidity" (Mongkolsuk, 1998). These values are highly site-specific however, thus the amount of data collection required generally makes the use of thresholds in LCAs prohibitive.

LCA results may also have limited value in two areas, that of local or **transient processes**, and on issues involving **biological parameters**, such as toxicity (Owens, 1997a). Sophisticated models, which include such details as environmental half lives, are presently only available for greenhouse gases and photochemical ozone depletion, while simple models, which assume 100% acidity, are used for acidification. Universal models are currently used in the determination of eutrophication indicators, which may not be valid for this site-specific effect. Thus the degree of uncertainty varies significantly between impact categories.

Mechanisms are the basis for the characterisation models (Owens, 1996), and these environmental mechanisms and processes are highly complex. Global, long-lived processes have characteristics that can be handled with a more acceptable theoretical accuracy than those which are more transient and local. Thus results relating to the latter type of processes should be used with caution, and preferably be supported by additional information. The potential accuracy of impact categories based on their inherent characteristics are given in Table 5.4 (Owens, 1996).

Impact Category	Spatial	Temporal	Dose Response	Threshold	Accuracy
Greenhouse effect	Global	Centuries/ decades	Linear (?)	No (?)	Good
Stratospheric ozone depletion	Global	Centuries/ decades	Linear	No	Good
Acidification	Continental/ regional	Years	Non-linear	Yes	Fair
Eutrophication	Regional/ local	Years	Approx. linear	Yes	Fair-poor
Photochemical smog	Regional/ local	Hours/day	Very non-linear	No (?)	Poor
Ecotoxicity	Local	Hours-years	Non-linear	Yes	Poor
Habitat loss	Regional (?)/ local	Decades/ years	Non-linear	Yes	Very poor
Biodiversity	Regional (?)/ local	Years	Non-linear	Yes	Very poor

Table 5.4: Potential accuracy of impact categories based on inherent characteristics (Owens, 1997b).

Where "?" indicates some uncertainty in the answer.

Simultaneous exposure to all emissions (regardless of time or place where release occurs) is assumed, and the effects are assumed to be additive. Thus it is evident that **spatial and temporal considerations** are largely lost, because details regarding the emission are currently excluded (atmospheric transport, transformation kinetics, frequency, duration, magnitude of average exposure, peak exposures, point or diffuse sources of emissions, and recipient sensitivity, for example). A single, global exposure is assumed. Currently LCA provides a worst case scenario, as it implies that all emissions take place at sensitive sites, and that all emissions cause effects (only a zero emission would have no impact) (Owens, 1997b).

It is thus evident that the limitations in the classification methodology currently employed arise from the aggregation of emission and resource use impacts over time and from different places in a LCA, and the assumptions that no thresholds exist, and that all loading responses are linear. It should be noted, however, that these limitations are in the process of being addressed (Guinée, *et al*, 1996, and 1998).

5.3.5) Environmental profiles for Impala's BMR

The overall average LCI input and output data, as given in Table 4.2, was entered into PEMS version 4 software, as was the monthly data in Appendix 1. Masses were entered in kg, and electricity in MJ. The functional unit used was a ton of nickel produced, as discussed in section 3.6, and the system boundaries were those defined in section 3.3.

The natural gas (UK) database from PEMS was used as a first approximation of the impacts incurred in the production of Sasol gas from coal, although it is acknowledged that the processing technologies are significantly different. Similarly, the hard coal (UK) data was used, as no local data was available and this database represented South African coal better than the alternative database relating to lignite (brown coal) (Notten, 1998). It is assumed that the mining and beneficiation (washing) processes are comparable, although it is acknowledged that the composition of the coal is different. A South African LCI database for electricity generation was used (Notten, 1998).

The electricity consumption was entered as a total, due to the lack of detailed metering. For the details which were available, refer to section 4.4. The effluent is shown separately, as the combined effluent from the BMR and the steam generation processes is routed to Ergo. The rainfall which is a component of the effluent was included (it was also included in the water impact category), and the outputs were in terms of evaporative losses from the pond, waste water output (to Ergo), as well as the emission of metal (Ni, Cu, Co) cations and associated anions (ammonia and sulphate) to water. This served as a worst case scenario, in which the ions migrate to the groundwater while the effluent is in use by Ergo. (Note: the effluent balance does not close due to the fluctuating pond level). The jarosite output is entered as a mass to landfill only, as leachability testwork has been done to ensure that pre-treatment of the waste is sufficient. In addition, the landfill site is certified to safely dispose of this waste, in that all leachable constituents are contained.

The overall average environmental profile thus obtained is presented in Table 5.5, while Appendix 4 contains a detailed table of the PEMS inputs. Appendix 5 contains examples of the classification calculations for the contributions of steam

generation (including coal usage) and electricity generation to the greenhouse effect, resource depletion, and smog impact categories. The mass (in kg) of each relevant substance from the LCI per ton of nickel produced is multiplied by the corresponding classification factor to derive the impact scores, which are then totalled.

The contributions of reagent inputs to the impacts can be seen from Table 5.5 (generally the largest impacts in this regard were due to ammonia, although a significant amount of water was used during O_2 manufacture). The boiler combustion products (from steam and electricity generation) contributed significantly to many of the impact categories, as is evident from Figure 5.1, which shows the percentage contributions of the main processes to the total impact category scores. The totals for each environmental impact category may be used in the comparison of the potential environmental impacts of alternative processes to this base case (as will be demonstrated in Chapters 7, 8 and 9).

Figure 5.2 shows the variation in the monthly environmental profiles for the period January 1995 to July 1997. It is evident that there were significant deviations from the overall average for all impact categories. These environmental profiles will be discussed further in Chapter 6.

Impact category	TOTAL	BMR total	BMR process	O_2 from air decomposition	N_2 from air decomposition	H_2SO_4	HNO_3	Ammonia	H_2 total	H_2 produced	Natural gas delivered UK	Steam total	Steam generated	Coal, hard UK	SA elec	Effluent
GWP (kg CO_2)	**26611**	**2566**	0.00	354	168	288	39	1717	**1063**	893	170	**16442**	14365	2077	**6541**	**0.00**
Water in (kg)	**153044**	**56442**	21098	15654	7412	6615	147	5516	**923**	0.00	923	**69778**	42060	27718	**12259**	**13643**
Resource depletion (/year)	**60.9**	**14.9**	0.00	1.24	0.59	1.36	0.25	11.5	**11.95**	0.00	12.0	**27.7**	0.00	27.7	**6.31**	**0.00**
Acidification (kg SO_2)	**308**	**22.3**	0.00	2.22	1.05	7.30	0.28	11.4	**0.96**	0.00	0.96	**203**	198.8	3.84	**82.2**	**0.00**
Ecotoxicity (Aquatic m^3)	**4.88**	**0.03**	0.00	0.01	0.005	0.01	0.00	0.01	**0.02**	0.00	0.02	**0.72**	0.00	0.72	**0.79**	**3.33**
Ecotoxicity (Terrestrial m^3)	**2.38E-02**	**1.33E-02**	0.00E+00	3.87E-03	1.83E-03	3.22E-03	1.42E-04	4.25E-03	**1.21E-03**	0.00E+00	1.21E-03	**9.30E-03**	0.00E+00	9.30E-03	**9.01E-07**	**0.00E+00**
Eutrophication (kg PO_4)	**56.2**	**1.80**	0.00	0.10	0.05	0.07	0.04	1.54	**0.09**	0.00	0.09	**37.4**	29.6	7.76	**2.71**	**14.2**
Human Toxicity (kg/kg)	**406**	**32.6**	0.00	3.29	1.56	9.12	0.40	18.2	**1.62**	0.00	1.62	**231**	225	6.44	**139**	**1.23**
Ozone depletion (kg CFC 11)	**5.91E-04**	**3.38E-04**	0.00E+00	8.25E-05	3.91E-05	5.28E-05	3.59E-06	1.60E-04	**9.17E-05**	0.00E+00	9.17E-05	**1.61E-04**	0.00E+00	1.61E-04	**0.00E+00**	**0.00E+00**
Smog (kg ethene)	**12.7**	**2.45**	0.00	0.08	0.04	0.06	0.041	2.23	**0.13**	0.00	0.13	**0.78**	0.00	0.78	**9.30**	**0.00**
Smog (kg NO_x)	**259**	**8.04**	0.00	0.71	0.34	0.52	0.19	6.29	**0.59**	0.00	0.59	**230**	228	2.02	**20.6**	**0.00**

Table 5.5: Overall impact assessment for the production of one ton of nickel at Impala Platinum Ltd, BMR.

Figure 5.1: Percentage contributions of processes to the overall average impact assessment for Impala Platinum Ltd, BMR

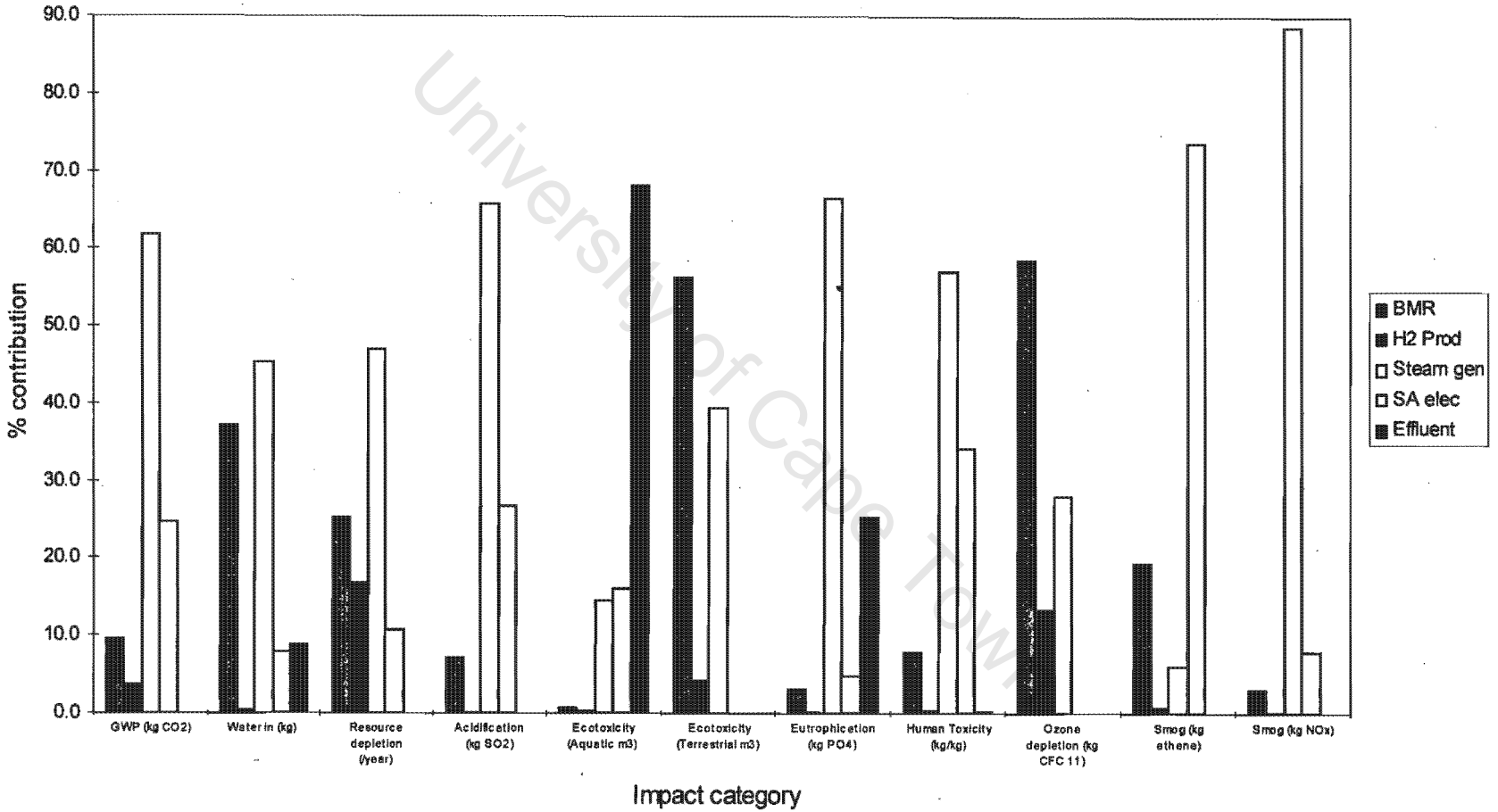
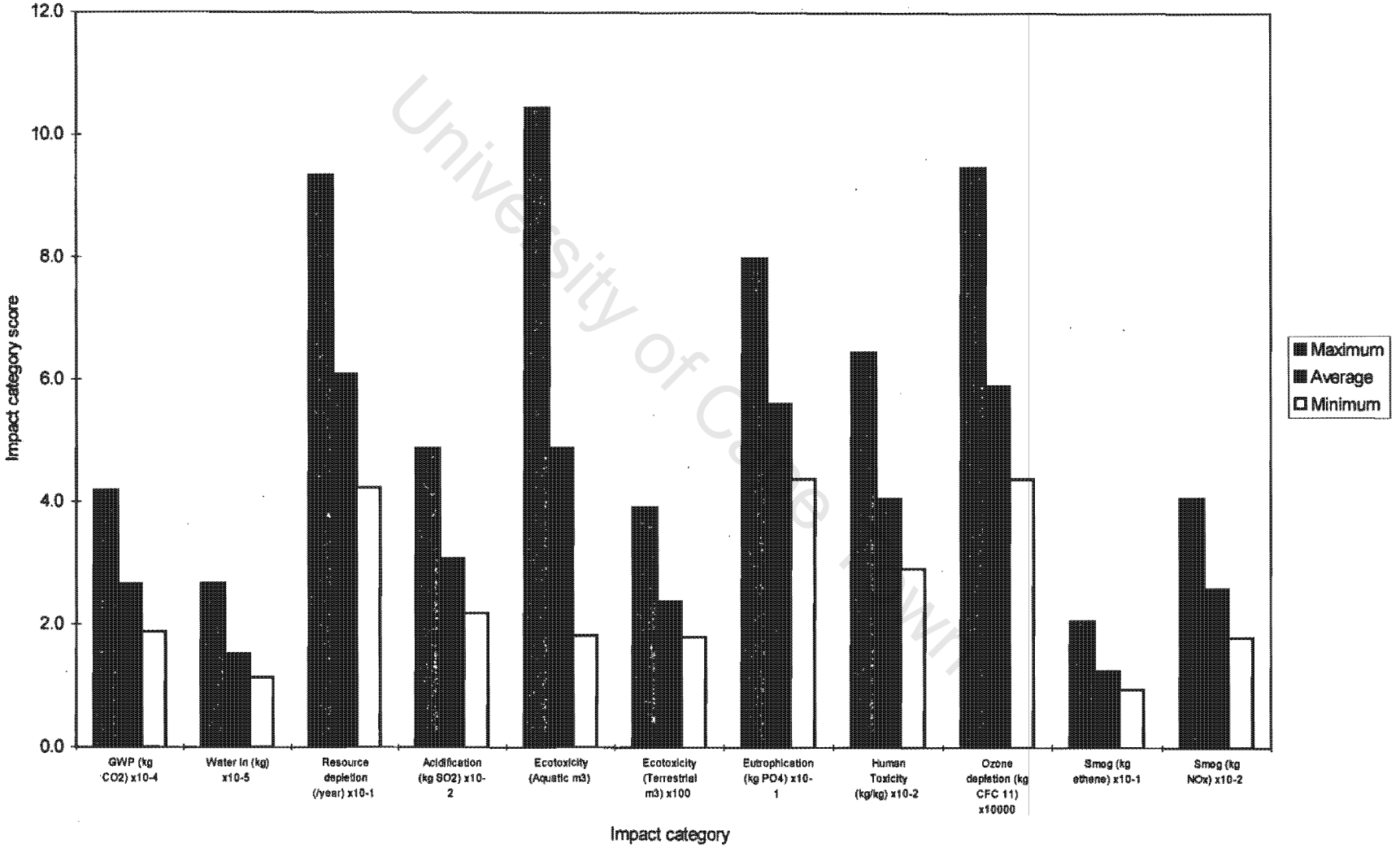


Figure 5.2: Monthly variation in impact profiles



5.4) NORMALISATION

5.4.1) Introduction

Effect scores may be normalised to convert them to relative contributions, although this introduces additional uncertainty into the assessment. Data is normalised in relation to a reference, which may be an annual global value, an industry average, a legal threshold, or an economic expression such as prevention costs (Weidema, 1993; Sørensen, 1996).

Another developing normalisation technique is the Unilever Imprint Methodology, which is used "to estimate the potential total environmental impact of all (Unilever's) products, in the context of Unilever's contribution to the world economy" (Unilever, 1999). This method involves scaling the total impact category scores derived from Unilever's operations, to impact per $ Net Proceeds of Sales of the company. These are then compared to the global impacts per $ of Global Gross Domestic Product, which are derived from published data and best estimates (Unilever, 1999).

The normalisation reference used by PEMS is the annual global effect score for the following five impact categories: resource depletion, greenhouse effect (direct), acidification, eutrophication, and smog. Regional scaling in normalisation would be more useful and the uncertainty lower, however, for regional impact problems, such as water use, acidification, smog, and eutrophication (Vigon, 1997d).

The results of the normalisation step should be considered provisional because of lack of adequate data. The PEMS manual, for example, states that "this normalisation data is somewhat approximate as it has been factored up from Dutch generated data and is based on 1992 emissions" (Pira, 1998).

5.4.2) Local water consumption

This impact category serves to demonstrate how the normalisation step could be carried out for a local or regional environmental concern. In order to obtain regional data on water consumption for use in normalisation, information on monthly water consumptions by medium-sized industries (in terms of the consumption of >300kℓ of water per month) in the Springs area was obtained from the Rand Water Board (RWB) and Springs Municipality (four of the industries, including Impala, purchase

water directly from the RWB). These values are summarised in Table 5.6. Domestic and small industry consumptions were excluded, as they were orders of magnitude smaller, and the consumption of two large industries in the area (which consume over 100Mℓ of water each per month) are given separately. Totals only are given, as detailed individual industry consumptions could not be stated for confidentiality reasons.

	94/95	95/96	96/97
Average monthly consumption (medium-sized consumers)	566	487	473
Number of medium consumers	63	56	51
Average monthly consumption (large consumers)	465	472	572
Total average monthly consumption	1031	959	1045
Average monthly Impala Refineries consumption	65	58	60
Average Impala Refineries consumption per ton of Ni produced	76.9	56.3	56.1
Impala as % of total medium-sized consumption	11%	12%	13%
Impala as % of total consumption	6%	6%	6%

Table 5.6: Springs water consumption data.

Units in Mℓ, unless otherwise stated.

Upon comparison of the total average water consumption with the total consumption by industry in South Africa in Table 5.3, it is evident that industry in the Springs area contributes to approximately 1% of the total. Thus Impala consumes roughly 0.06% of the total water consumed by the industrial sector in South Africa.

Although Impala's consumption generally decreased during the time period considered (the increase from 95/96 to 96/97 was due to increased water and steam requirements by the PMR, resulting from a change in technology), its percentage contribution to the consumption of medium industries increased because this total also decreased over time as a consequence of a decrease in the

number of medium-sized industries (refer to Table 5.6). The use of the ratio of Impala's water consumption to the overall total (Springs) or to the total consumption by medium industries, to normalise the water consumption impact category would thus mask the decrease in consumption that Impala has achieved. The water usage impact category is therefore not normalised. Overall, Impala was the 7th largest industrial consumer of water in the Springs area (based on monthly average consumption) over this time period. Unfortunately, there are no similar refining operations in the area with which to compare Impala's water consumption (water consumption is a function of process technology).

5.4.3) Normalised environmental profile of Impala's BMR

The normalised environmental profile relating to the overall average LCI is given in Table 5.8 and Figure 5.3. The normalisation factors used (from PEMS software) are listed in Table 5.7. It is noted that a number of impact categories are not included due to a lack of normalisation data, which limits the usefulness of the resulting profile. The normalisation factor for resource depletion has a value of one because the inverse of the reserve quantity of each resource was used in the classification process. The normalised profile indicates that resource depletion and smog generation are the environmental problems which the process studied could contribute to the most.

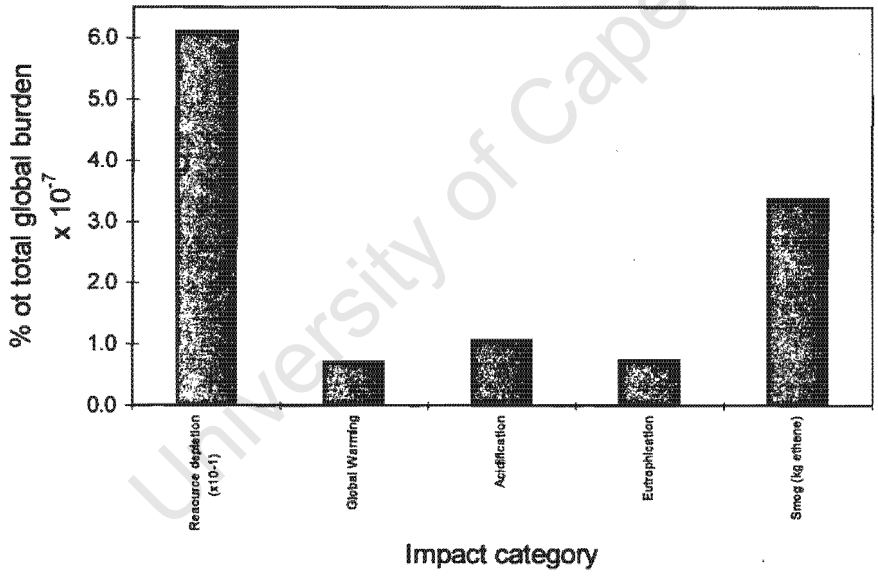
IMPACT CATEGORY	NORMALISATION FACTOR ($X10^{-9}$)
Resource depletion	1
Global warming	37700
Acidification	286
Eutrophication	74.8
Smog (kg ethene)	3.74

Table 5.7: Normalisation factors derived from annual global effect scores.

IMPACT CATEGORY	NORMALISED SCORE $X10^{-7}$%
Resource depletion ($x10^{-1}$)	6.1
Global warming	0.71
Acidification	1.1
Eutrophication	0.75
Smog (kg ethene)	3.4

Table 5.8: Normalised overall average impact scores, as a percentage of the global contributions.

Figure 5.3: Normalised overall average impact assessment



5.5) VALUATION

In order to evaluate the environmental profile, an environmental index may be created by making use of weighting factors. These weighting factors may be derived using either monetary methods, social preferences, modelling eventual effects, or by the application of sustainability principles.

Monetary methods may be effects-oriented (that is, the damage caused is expressed in monetary terms), or it may be source-oriented where the costs required to prevent effects are considered. A number of disadvantages are inherent with monetary methods, including the fact that it is impossible to quantify depletion and damage. The costs of avoiding an emission also do not relate to its seriousness, and would depend on the current technological development level (Heijungs, 1992b). Societal preferences assess the significance of a problem considering its current magnitude, the annual increase in the problem, the difficulty in controlling the problem, and its perceived significance (Heijungs, 1992b).

The desirability of having a generic weighting set for all LCA studies stems from the need for ease of comparison between studies, and to avoid the cost and time of deriving weighting sets for each study. Bias would also be avoided. The feasibility of establishing such a generic weighting set is hindered by the fact that the values would have to be static over time, and not be influenced by the actual application or circumstances. It is therefore unlikely that a generic weighting set will be agreed upon (Vigon, 1998b).

A number of methods have been developed which serve to aggregate impacts into a single score or index. These include the **Swiss Ecopoints** system, related to Swiss governmental policy standards (Guinée, 1994), the **CML** method, in which environmental issues are selected and weighted according to their perceived environmental priority (Vigon, 1998d), and the American **Tellus** Institute method, in which emissions are aggregated based on prevention or recovery costs (Guinée, 1994). The Swedish **EPS** (Environmental Priority Strategies for Product Design) method aggregates emissions and resource use into one index based on the willingness to pay to avoid the environmental degradation in relation to five "safeguard subjects" (biodiversity, production, human health, resources, and aesthetic values) (Graedel, 1994).

Valuation methods are inherently subjective, thus the significance of the results of such methods should be viewed with some degree of caution. The valuation step was thus not performed in this study. (For a more detailed account of this topic, refer to Volkwein, *et al*, 1996a and 1996b).

5.6) SUMMARY OF FINDINGS

From the environmental profile generated for the Base Metal Refinery of Impala Platinum Ltd, it was evident that steam and electricity generation were the most significant sources of environmental impacts. With respect to reagent usage, the greatest potential contribution to environmental impacts were those associated with the manufacture of ammonia. The current usage of the BMR effluent by Ergo could result in ecotoxicity and eutrophication impacts.

The normalised impact scores indicated that the potential contributions to resource depletion and smog were the most significant when compared to the global contributions to the impact categories, although it is noted that a number of impact categories were excluded from this normalisation step.

Chapter 6: IMPROVEMENT ASSESSMENT

6.1) INTRODUCTION

The environmental profiles generated in Chapter 5 can be used to assess areas of potential improvement with respect to environmental performance. The effects of data uncertainties and assumptions on the outcome of the results from the classification stage should be estimated, however, by means of sensitivity analyses. The effect of including reagents and the transportation of materials and reagents on the environmental profile was thus investigated, in order to determine whether the initial assumption to exclude these from the LCA was valid. Dominance analyses were then used to identify stages in the life cycle which were responsible for the majority of impacts on the environment.

6.2) SENSITIVITY ANALYSIS

6.2.1) The contribution of transport to the environmental profile

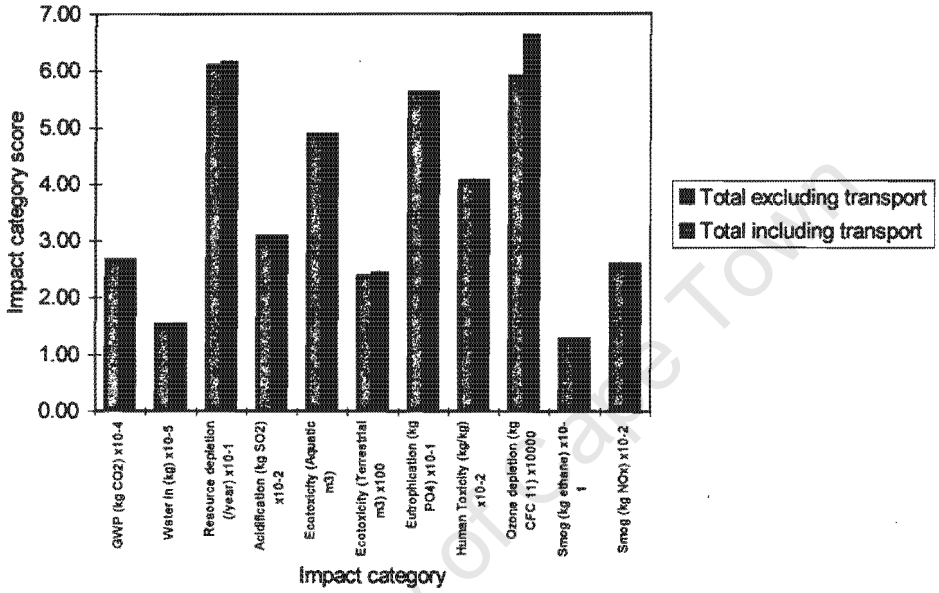
The transportation of materials and reagents may lead to significant potential environmental impacts due to fuel combustion emissions and resource usage. The effect of including the transport of Impala matte (the major raw material input) and the bulk reagents to the BMR site in the LCA were thus considered. The transportation option used from the PEMS database, was transportation by articulated truck via average road (part urban road, part rural road, and part motorway).

For the matte, which is transported 420km (for a round trip), trucks of capacity >33t are used. The PEMS database incorporates a 25t useful load for such a truck, but the actual capacity used is on average 29t, thus the distance travelled was reduced by a factor of 0.86 (that is, 25/29), giving a distance of 362km. The bulk reagents (sulphuric acid, nitric acid, and ammonia) are transported to the BMR site in trucks of capacity <33t, and it was assumed that the useful load as given in PEMS of 21t was a true representation of the utilised load. In addition, the engine capacities of the trucks is assumed to be the same. The distances involved with delivery were given in section 4.4.2.

The results of including these transportation steps are given in Figure 6.1 and Table 6.1, from which it is evident that transport contributes primarily to the resource

depletion, terrestrial ecotoxicity, smog, and greenhouse effect impact categories (in terms of an absolute change). The percentage change in the ozone depletion category was large due to the low absolute values (refer to Table 6.1). The changes were generally less than 5% and are thus not considered to be significant, therefore the exclusion of transport in the LCA is deemed to be a valid assumption.

Figure 6.1: The effect of including transport in the overall average impact assessment



IMPACT CATEGORY	TOTAL EXCLUDING TRANSPORT	TOTAL INCLUDING TRANSPORT	% DIFFERENCE
GWP (kg CO_2) ($x10^{-4}$)	2.66	2.67	0.4
Water in (kg) ($x10^{-5}$)	1.53	1.53	0
Resource depletion (/year) ($x10^{-1}$)	6.09	6.15	1.0
Acidification (kg SO_2) ($x10^{-2}$)	3.08	3.08	0
Ecotoxicity (Aquatic m^3)	4.88	4.89	0.2
Ecotoxicity (Terrestrial m^3) ($x10^{2}$)	2.38	2.43	2.1
Eutrophication (kg PO_4) ($x10^{-1}$)	5.62	5.62	0
Human Toxicity (kg/kg) ($x10^{-2}$)	4.06	4.07	0.2
Ozone depletion (kg CFC 11) ($x10^{4}$)	5.91	6.62	12.0
Smog (kg ethene) ($x10^{-1}$)	1.27	1.28	0.8
Smog (kg NO_x) ($x10^{-2}$)	2.59	2.60	0.4

Table 6.1: Overall average impact assessment data, including and excluding transport.

6.2.2) The contribution of previously excluded reagents to the environmental profile

In order to validate the exclusion of the reagents, as listed in Table 4.5, the effect of the inclusion of these reagents on the environmental profile was determined. Firstly, the reagent with the highest consumption, sulphur dioxide, was included. Due to the fact that PEMS version 4 database does not contain sulphur dioxide as an input option, the sulphuric acid data was modified to generate an approximate LCI for SO_2, because sulphur dioxide is a precursor in the production of sulphuric acid via the Contact Process (Austin, 1984). The relevant reactions are:

$$S + O_2 \rightarrow SO_2 \qquad (a)$$

$$SO_2 + \tfrac{1}{2} O_2 \rightarrow SO_3 \qquad (b)$$

$$SO_3 + H_2O \rightarrow H_2SO_4 \qquad (c)$$

The quantity of sulphur dioxide which would have to be generated to produce 1000kg of H_2SO_4 (the reference quantity in the PEMS database) was calculated, and the amount of oxygen thus required was derived from reaction (a). It was estimated that half of the steam by-product would be produced compared to that for sulphuric acid generation, because the enthalpy of reaction (a) is approximately equivalent to that of reaction (b) plus reaction (c). The water input as given in the sulphuric acid database was thus decreased by the amount consumed in reaction (c) and by this difference in water consumption for steam generation. The environmental profile which was generated is presented in Table 6.2, from which it is evident that the inclusion of sulphur dioxide in the LCA did not significantly alter the impact scores. The same profile scores were obtained as those shown in Table 6.2 when the entire sulphuric acid database was used for SO_2 (only very small changes at high decimals occurred). This confirms the result, as it provides a worst case scenario where all potential environmental impacts incurred in sulphuric acid manufacture are attributed to SO_2.

Similarly, a number of other previously excluded reagents from Table 4.5 were included, based on the availability of LCI information regarding their manufacture from the PEMS database. The following reagents were thus included: sulphur dioxide, sodium chloride, sodium hydroxide, hydrochloric acid and ferrous sulphate. The environmental profile thus obtained, as shown in Table 6.3, reflects increases in the potential impacts which were all well below 1%. It was thus concluded that

the exclusion of these reagents was a valid assumption, and that the exclusion criteria were appropriate (refer to section 3.3.2).

IMPACT CATEGORY	AVERAGE	AVERAGE INCLUDING SO_2	% CHANGE
GWP (kg CO_2) ($x10^{-4}$)	2.66	2.66	0
Water in (kg) ($x10^{-5}$)	1.53	1.53	0
Resource depletion (/year) ($x10^{-1}$)	6.09	6.10	0.2
Acidification (kg SO_2) ($x10^{-2}$)	3.08	3.08	0
Ecotoxicity (Aquatic m^3)	4.88	4.88	0
Ecotoxicity (Terrestrial m^3) ($x10^{2}$)	2.38	2.40	0.8
Eutrophication (kg PO_4) ($x10^{-1}$)	5.62	5.62	0
Human Toxicity (kg/kg) ($x10^{-2}$)	4.06	4.06	0
Ozone depletion (kg CFC 11) ($x10^{4}$)	5.91	5.93	0.3
Smog (kg ethene) ($x10^{-1}$)	1.27	1.27	0
Smog (kg NO_x) ($x10^{-2}$)	2.59	2.59	0

Table 6.2: The effect of the inclusion of sulphur dioxide in the LCI.

IMPACT CATEGORY	AVERAGE	AVERAGE: INCLUDING ADDITIONAL REAGENTS	% CHANGE
GWP (kg CO_2) ($x10^{-4}$)	2.66	2.66	0
Water in (kg) ($x10^{-5}$)	1.53	1.53	0
Resource depletion (/year) ($x10^{-1}$)	6.09	6.11	0.3
Acidification (kg SO_2) ($x10^{-2}$)	3.08	3.09	0.3
Ecotoxicity (Aquatic m^3)	4.88	4.89	0.2
Ecotoxicity (Terrestrial m^3) ($x10^{2}$)	2.38	2.40	0.8
Eutrophication (kg PO_4) ($x10^{-1}$)	5.62	5.62	0
Human Toxicity (kg/kg) ($x10^{-2}$)	4.06	4.07	0.2
Ozone depletion (kg CFC 11) ($x10^{4}$)	5.91	5.93	0.3
Smog (kg ethene) ($x10^{-1}$)	1.27	1.27	0
Smog (kg NO_x) ($x10^{-2}$)	2.59	2.60	0.4

Table 6.3: The effect of including additional reagents on the environmental profile.

6.2.3) The relationship between impact category scores and the functional unit

The monthly environmental profiles, as presented in Figure 5.2, indicated that the impact category effect scores (per ton of nickel produced) were not constant, but varied from month to month. The relationship between these scores and the quantity of nickel produced was thus investigated, as shown in Figures 6.2 to 6.12.

Figure 6.2: The relationship between the greenhouse effect impact category and nickel production

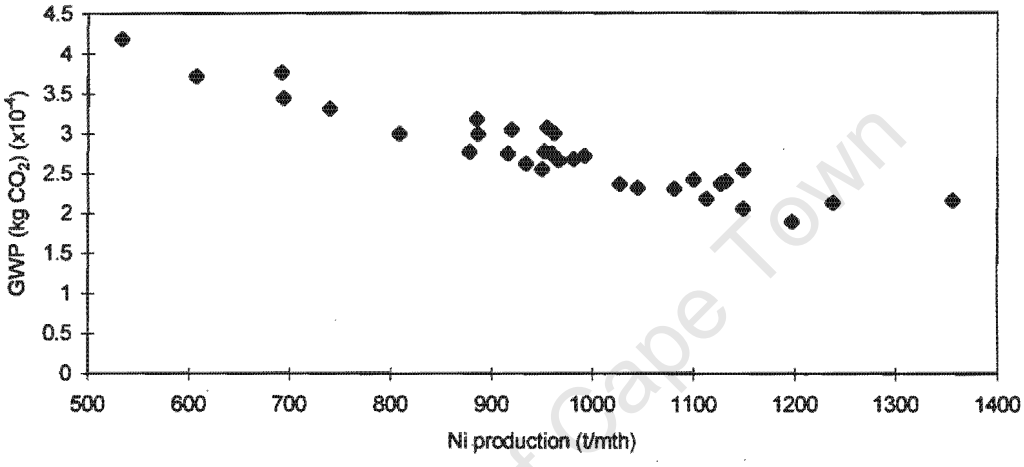


Figure 6.3: The relationship between the water usage impact category and nickel production

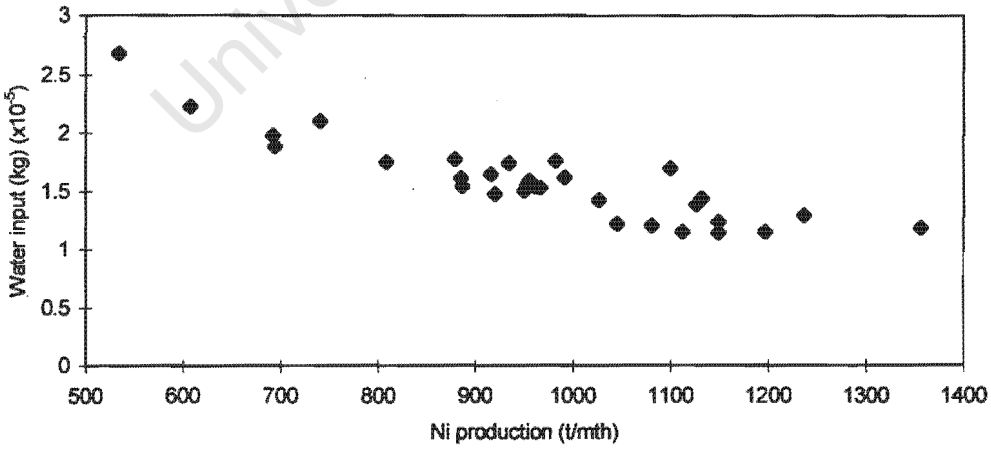


Figure 6.4: The relationship between the resource depletion impact category and nickel production

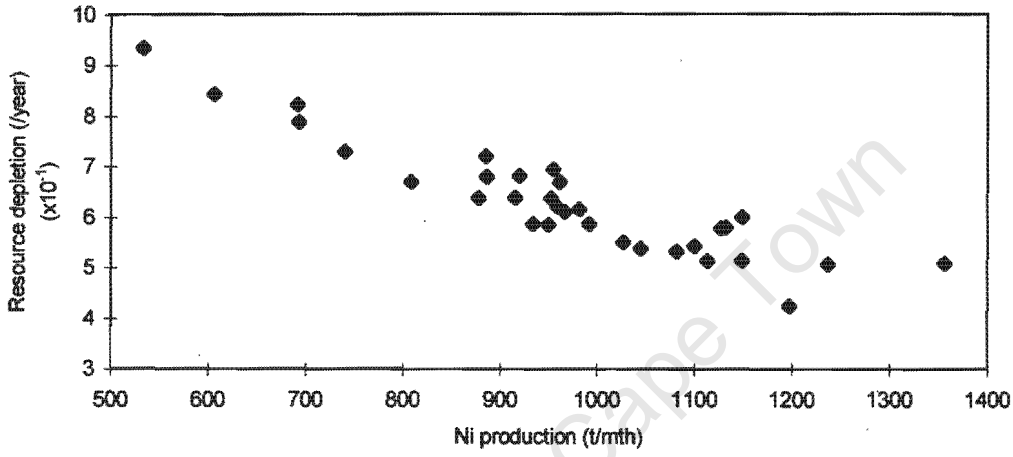


Figure 6.5: The relationship between the acidification impact category and nickel production

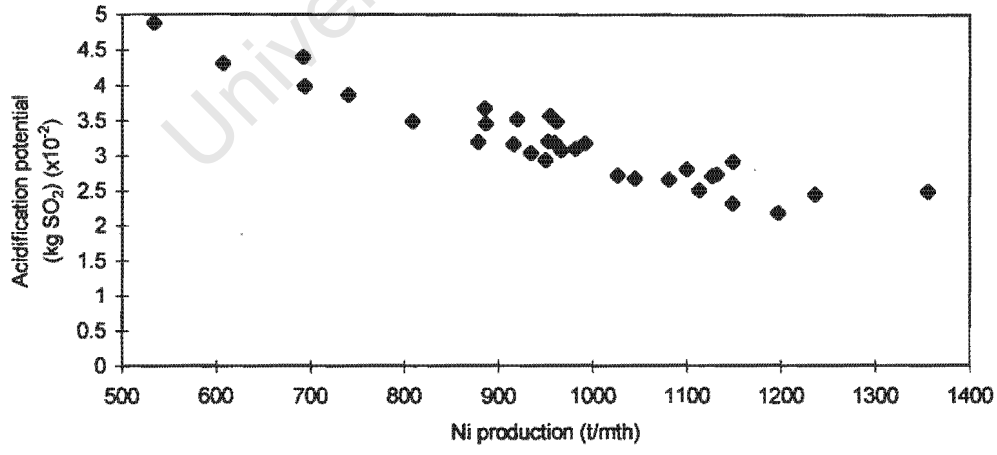


Figure 6.6: The relationship between the aquatic ecotoxicity impact category and nickel production

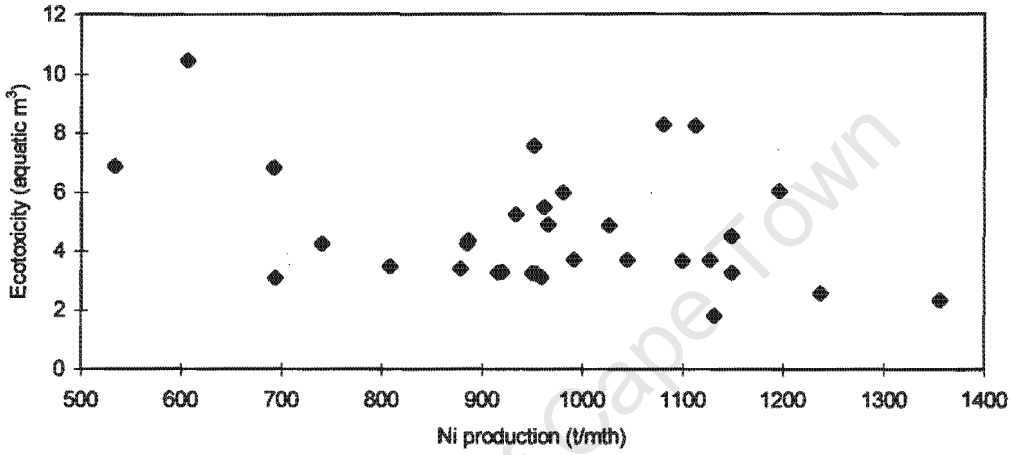


Figure 6.7: The relationship between the terrestrial ecotoxicity impact category and nickel production

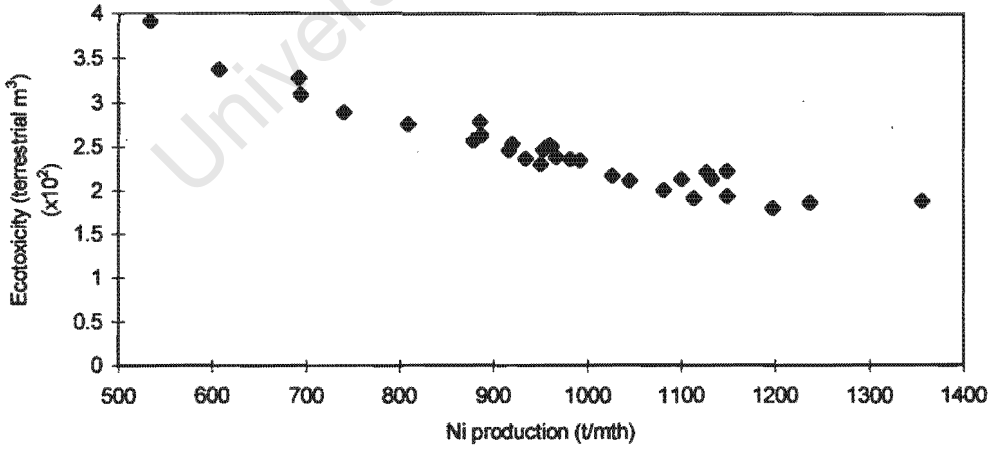


Figure 6.8: The relationship between the eutrophication impact category and nickel production

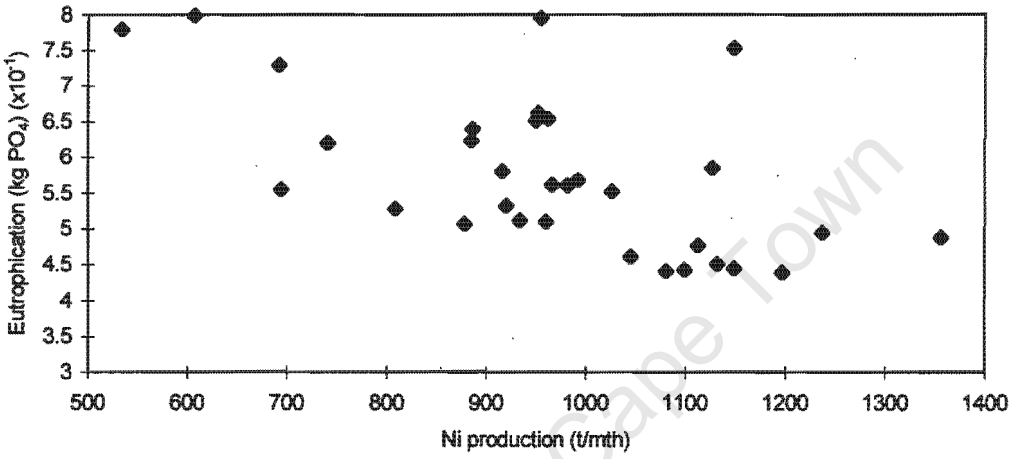


Figure 6.9: The relationship between the human toxicity impact category and nickel production

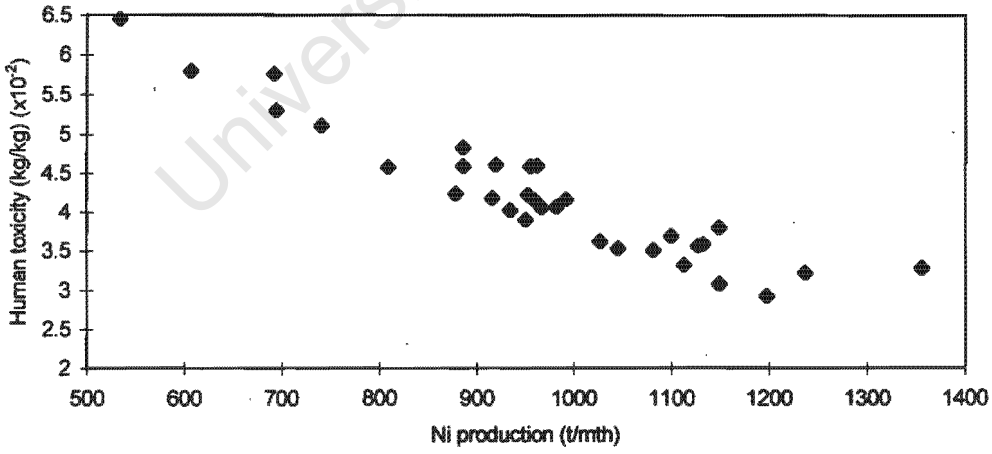


Figure 6.10: The relationship between the ozone depletion impact category and nickel production

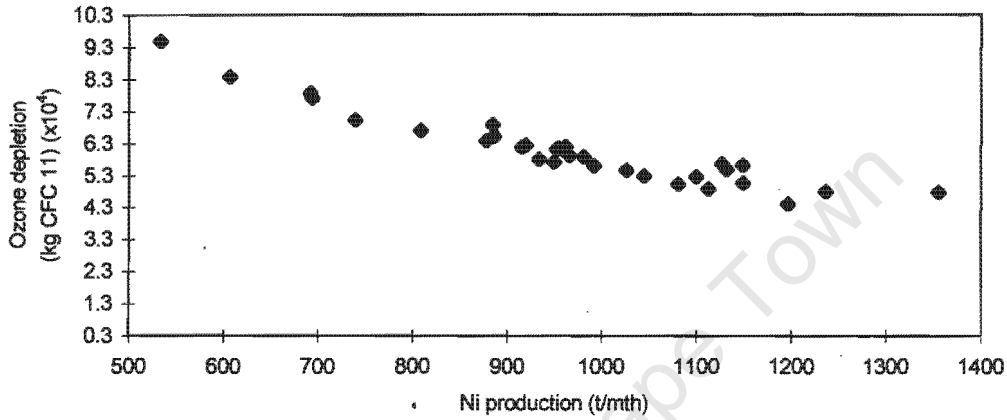


Figure 6.11: The relationship between the smog impact category (kg ethene) and nickel production

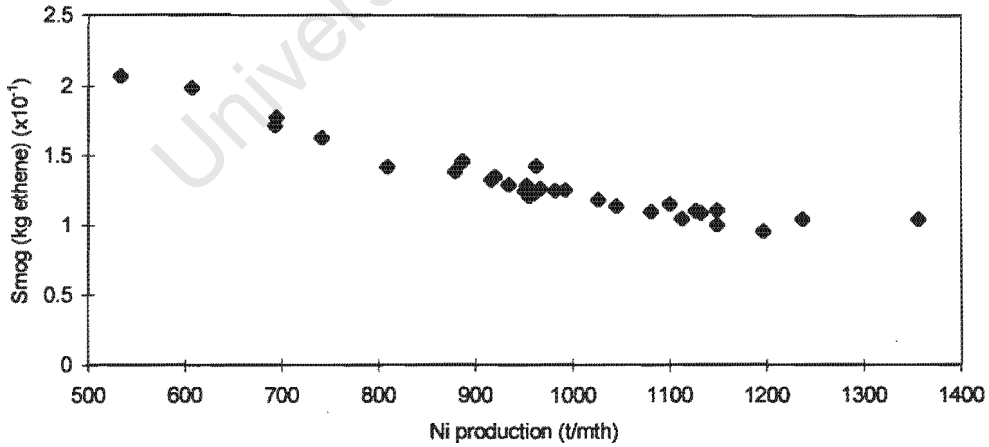
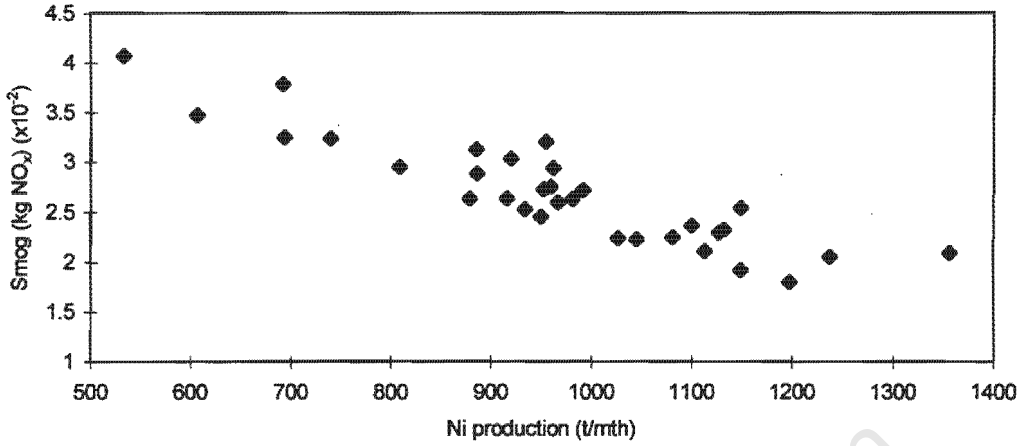


Figure 6.12: The relationship between the smog impact category (kg NO_x) and nickel production



It is evident from Figures 6.2 to 6.12 that the general trend is a decrease in impact per ton of nickel produced with an increase in nickel production (with the unit impact scores typically doubling over the Ni production range). This trend was not evident when these scores were multiplied by the monthly nickel productions to give the total impact score profiles, which varied randomly with nickel production. Due to the fact that the total impact scores were not significantly lower at low nickel production rates, the normalised scores (total score/t Ni produced) in this region were higher than those at higher nickel production rates, resulting in the trend of decreasing impact scores per ton of nickel produced with an increase in nickel production. It appears that Figures 6.2 to 6.12 may level off at high nickel production rates, but this would need to be confirmed by more data in this region. A function relating the environmental impacts to the amount of nickel produced could then be determined.

The trend of decreasing impact scores per ton of nickel produced was verified by the manual calculation of some of the impact scores for the months of highest and lowest nickel production rates, as shown in Appendix 5. The impact scores per ton of nickel produced of the steam generation (excluding the impacts associated with coal processing) and electricity generation processes (which were the dominating contributors to the impact scores) were higher for months of low nickel production, which indicates that the BMR process may operate less efficiently at low nickel production rates. Energy usage efficiencies, which contributed significantly to this trend, will be addressed in section 6.3.1. In terms of reagents; additions are generally based on process volumes and not on stoichiometry, which leads to less efficient usage of chemicals at low production rates.

The exceptions to this trend were the eutrophication and aquatic ecotoxicity impact categories (and to a lesser extent the smog (NO_x) category). The eutrophication impact category varied in a similar manner to the quantity of ammonia in the effluent output, which was not linear with respect to nickel production, as can be seen in Figure 6.13. Similarly, the aquatic ecotoxicity scores varied according to the quantity of nickel in the effluent (Figure 6.14). It is evident from the lack of trends in Figures 6.13 and 6.14 that the quality of the effluent is not strongly related to production volumes. The effluent quality fluctuates due to variation in rainfall (which has a diluting effect, because stormwater enters the effluent pond), and as a result of non-routine plant operation (which results in process liquor entering the effluent pond). This illustrates how critical it is that process staff be made aware of the possible environmental impacts of their actions.

Figure 6.13:Relationship between the quantity of ammonia in the effluent and nickel produced

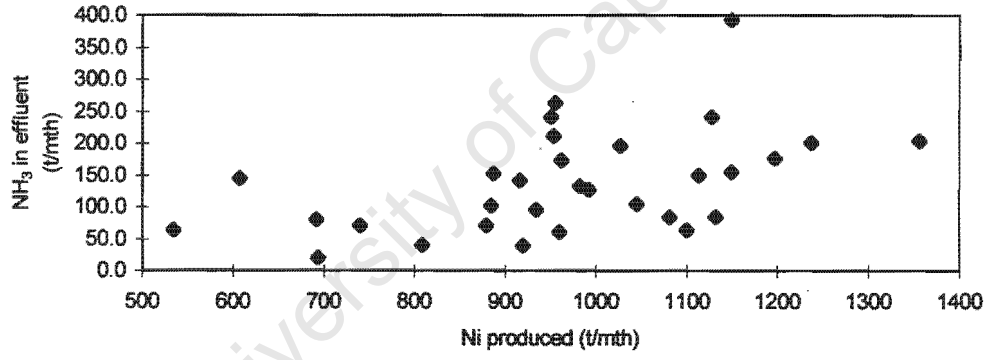
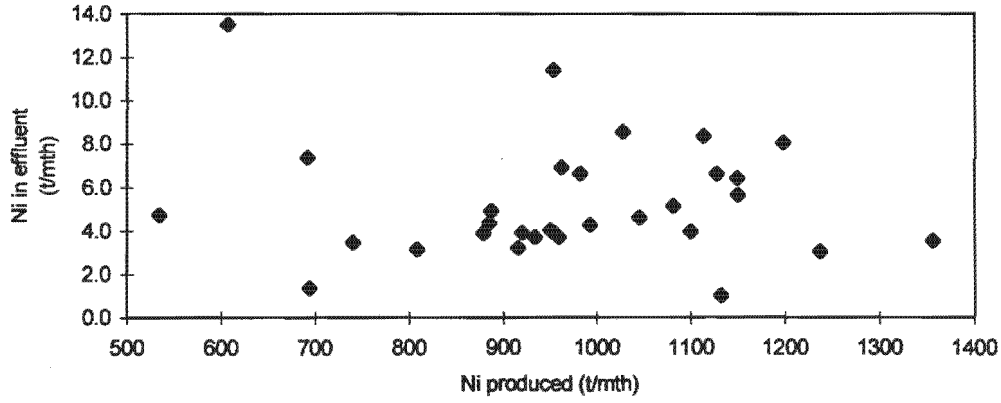


Figure 6.14: Relationship between the quantity of nickel in the effluent and nickel produced



(Note: The same trends were obtained when the months for which average reagent consumptions were used were excluded).

6.3) DOMINANCE ANALYSIS

6.3.1) The contribution of the steam generation process to the environmental profile

It is evident from Table 5.5 and Figure 5.1 that steam generation was the largest source of potential environmental impacts in most categories. The percentage contributions of the steam generation plant to each impact category considered is shown in Table 6.4.

IMPACT CATEGORY	TOTAL IMPACT SCORE	IMPACT SCORE FROM THE STEAM PLANT	% CONTRIBUTION FROM THE STEAM PLANT
GWP (kg CO_2)	26611	16442	62
Water in (kg)	153044	69778	46
Resource depletion (/year)	60.9	27.7	45
Acidification (kg SO_2)	308	203	66
Ecotoxicity (Aquatic m^3)	4.88	0.72	15
Ecotoxicity (Terrestrial m^3)	2.38E-02	9.30E-03	39
Eutrophication (kg PO_4)	56.2	37.4	67
Human Toxicity (kg/kg)	406	231	57
Ozone depletion (kg CFC 11)	5.91E-04	1.61E-04	27
Smog (kg ethene)	12.7	0.78	6
Smog (kg NO_x)	259	230	89

Table 6.4: The contribution of the steam generation plant to the environmental profile.

Due to the fact the BMR is a continuous operation, it has a large fixed energy load (Impala's management estimate that this contributes 70% of the total energy usage). This arises from maintaining the temperature of vessels (using steam) and providing agitation to prevent solids settling out of solution, regardless of throughput. The variable energy load arises primarily from the Co plant (which is a batch process) and in heating feed solutions. As a result of the large fixed energy requirements of the BMR, the steam and electricity efficiencies are more favourable at higher Ni throughputs. The boilers are also kept running continuously regardless of throughput (with the exception of maintenance downtime), to prevent equipment damage as a result of temperature fluctuations.

It is evident from the results that the largest improvements in environmental performance can be made by reducing or eliminating the impacts associated with the steam plant. Therefore, means of achieving this should be investigated, including alternatives to coal-burning (such as gas- or oil-fired boilers).

Atmospheric emissions from coal combustion may be controlled by the combustion parameters employed and/or by the addition of sorbents (to decrease SO_2 emissions) during the combustion process. Fluidized-bed combustion, for example, reduces emissions by controlling combustion parameters, while the injection of limestone captures sulphur (Noyes, 1993). A solid waste product (a mixture of calcium sulphite and calcium sulphate) is thus produced, which is removed from the boiler with the ash. Consequently, this secondary process may increase the environmental burden as well as increasing treatment and disposal costs (Powlesland, 1994). It is therefore more prudent to control emissions by using good quality coal (within the constraints of South African coal specifications), and by controlling the combustion parameters where feasible.

A large portion of the steam is lost through venting (around 50% of the steam used in the BMR process, which indicates a significant potential improvement in efficiency), thus the potential for recovery of steam which is vented from the nickel and cobalt reduction flash tanks is currently being investigated (Makwana, 1996). Most of the ammonia present in the flashed steam would also be removed from the vent gas, but the recovery of the ammonia in this solution would be uneconomical, although it could be recycled within the process. In this manner, emissions to the atmosphere would be reduced, and a decrease in water usage and a slight decrease in ammonia usage may result. In addition, steam generation from the hot condensate would require less heat, and thus less coal would need to be burned. Consequently, the environmental impacts per ton of nickel produced due to steam generation would decrease.

The efficiency of the boilers may also be optimised by improved measuring protocols (to verify the mass balance and to monitor combustion and heat exchange parameters), and subsequent comparison with the performance of other, similar boiler operations. Specifically, the NO_x emissions should be verified by

measurement, to determine if any of the nitrogen in the coal is emitted as nitrogen gas and to quantify the amount of thermal NO_x produced.

6.3.2) The contribution of electricity to the environmental profile

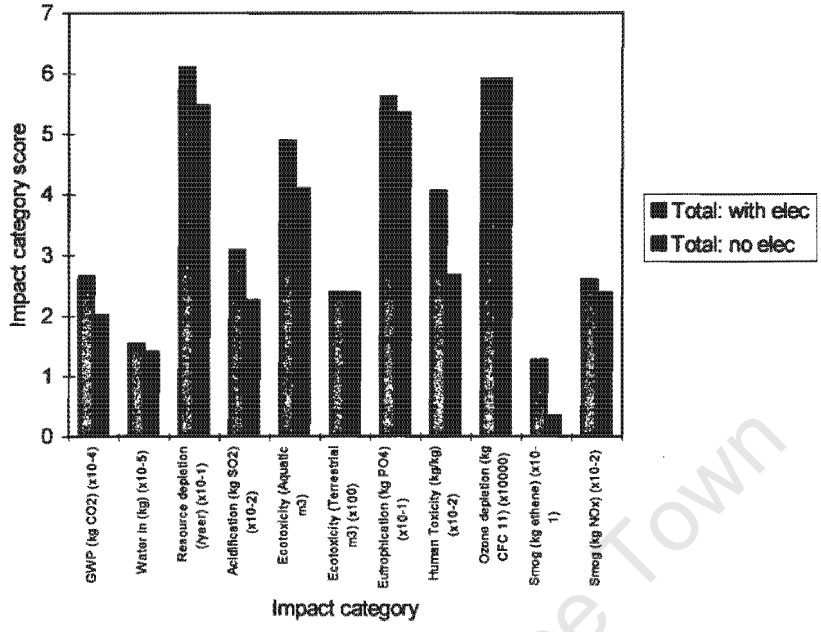
The contribution of electricity to the environmental impacts in the BMR case study, as presented in Table 5.5, is shown graphically in Figure 6.15, and the percentage contributions of electricity to each impact category are given in Table 6.5.

It is evident that electricity generation contributes significantly to the human toxicity, greenhouse effect, acidification, aquatic ecotoxicity, and smog (ethene) impact categories. It would thus be recommended that Impala reduce electricity consumption, where possible, by the installation of additional electricity meters to enable better monitoring of electricity use. Through this, areas of high consumption can be identified and possible improvements investigated. In this manner these potential impacts associated with electricity could be reduced, and cost savings could be made. The importance of taking such steps is evident from the fact that an environmental levy on energy sales in South Africa has been proposed in a draft White Paper on energy policy, in order to support alternative energy options and to promote energy efficiency (Ensor, 1998).

IMPACT CATEGORY	ELECTRICITY	TOTAL	ELECTRICITY AS A % OF TOTAL
GWP (kg CO_2)	6541	26611	25
Water in (kg)	12259	153044	8.0
Resource depletion (/year)	6.31	60.9	10
Acidification (kg SO_2)	82.2	308	27
Ecotoxicity (Aquatic m^3)	0.79	4.88	16
Ecotoxicity (Terrestrial m^3)	9.01E-07	2.38E-02	0.0
Eutrophication (kg PO_4)	2.71	56.2	4.8
Human Toxicity (kg/kg)	139	406	34
Ozone depletion (kg CFC 11)	0.00	5.91E-04	0.0
Smog (kg ethene)	9.30	12.7	73
Smog (kg NO_x)	20.6	259	8.0

Table 6.5: The contribution of electricity to the overall average environmental profile.

Figure 6.15: Comparison of the environmental profiles including and excluding electricity, respectively



6.3.3) The contribution of ammonia consumption to the environmental profile

In terms of the BMR process itself, ammonia production was the largest contributor to most of the impact categories (refer to Table 5.5 and 6.6), while oxygen generation contributed the most to the water usage category (although this related to only 10% of the overall water consumption).

IMPACT CATEGORY	NH_3	TOTAL	NH_3 AS A % OF TOTAL
GWP (kg CO_2)	1717	26611	6.5
Water in (kg)	5516	153044	3.6
Resource depletion (/year)	11.5	60.9	19
Acidification (kg SO_2)	11.4	308	3.7
Ecotoxicity (Aquatic m^3)	0.01	4.88	0.2
Ecotoxicity (Terrestrial m^3)	4.25E-03	2.38E-02	18
Eutrophication (kg PO_4)	1.54	56.2	2.7
Human Toxicity (kg/kg)	18.2	406	4.5
Ozone depletion (kg CFC 11)	1.60E-04	5.91E-04	27
Smog (kg ethene)	2.23	12.7	18
Smog (kg NO_x)	6.29	259	2.4

Table 6.6: The contribution of ammonia consumption to the overall environmental profile.

It is evident from the data in Table 6.6 that ammonia consumption contributed significantly to the resource depletion, terrestrial ecotoxicity, ozone depletion, and smog (ethene) impact categories. Ammonia consumption should thus be optimised and wastage such as fugitive emissions minimised. The environmental profile and specifically these impact categories are therefore sensitive to changes in ammonia consumption, thus the quality of the consumption data is important to ensure that a representative environmental profile is generated.

6.4) CONCLUDING REMARKS

The exclusion of transport steps and of those reagents which are used in relatively small quantities from the LCI was confirmed by sensitivity analyses. It was found that an environmental economy of scale was evident in that the environmental impact scores generally decreased with increased nickel production. This was a consequence of the high fixed energy load of the refinery, which results in poorer energy efficiencies at low production rates.

The main findings of the improvement assessment were that the steam generation process was the most significant source of potential environmental impacts in the BMR operations of Impala Platinum Ltd. Electricity generation, and to a lesser extent ammonia production, also contributed significantly to many of the impact categories. Efforts to improve environmental performance should thus focus on these areas.

An interesting finding was that the potential environmental impacts associated with the effluent discharged to Ergo seemed to vary inexplicably. This points to poor process control, which emphasises the need to train employees in the environmental aspects of their jobs and in the consequences of their actions. In collecting and analysing the data required for this study, a number of shortfalls with respect to measurement protocols were highlighted (particularly those relating to effluent and water). This is currently being addressed by the operations personnel.

In the remaining part of the thesis, the use of the life cycle environmental model in evaluating the environmental performance of various process options will be investigated by means of scenarios. These will deal with a change in material input, in process technology, and in waste management practice respectively.

Chapter 7: SCENARIO A: THE ENVIRONMENTAL IMPACTS ASSOCIATED WITH NICKEL SULPHATE PROCESSING, AS COMPARED TO MATTE.

7.1) INTRODUCTION

Nickel sulphate is toll refined by Impala's BMR for other base metal refineries which do not have the facilities to produce pure nickel metal, such as Western Platinum (refer to Figure 2.4 and related discussion). The environmental impacts associated with the processing of nickel sulphate as compared to Impala matte were investigated. Due to the difference in composition of these two materials, their processing requires different reagent and utility consumptions, thus the environmental impacts associated with each material were expected to be different.

As there were no months, during the period considered in this study, in which no nickel sulphate was processed, the contributions of matte and nickel sulphate to the various inputs and outputs of the LCI had to be estimated. The reagent and utility requirements were calculated using the overall average base case, in order to obtain the contribution of nickel sulphate processing to the average environmental profile of the BMR. The goal definition and scoping details were those discussed in Chapter 3, and data from Chapter 4 was used in the calculations.

The amount of nickel sulphate that is processed by the BMR is dependent upon toll refining commitments, in terms of required nickel production, and on available process capacity, as a certain quantity of matte must be processed in order to produce the required quantity of PGM concentrate for further processing by the PMR. It is assumed for the purposes of this case study, however, that the BMR could process solely nickel sulphate, in that the environmental impacts of nickel sulphate and matte treatment are separated.

7.2) DATA COLLECTION AND LCI

The nickel sulphate which is toll refined in the BMR has a different chemical composition to that of the matte. Notably, the nickel sulphate does not contain PGMs nor a significant quantity of copper, and it does not require pressure leaching

(it is added to the process post first stage leach, prior to copper cementation), thus the processing of nickel sulphate does not contribute to the reagent and utility requirements associated with these circuits. The unit operations (as defined in Figure 4.1 and Table 4.1) which are relevant to the processing of nickel sulphate were thus Jarosite (unit operation 3), Nickel purification and reduction (unit operation 4), Mixed double salts (unit operation 5), Cobalt purification and reduction (unit operation 6) and Ammonium sulphate (unit operation 7). This is illustrated in Figure 7.1.

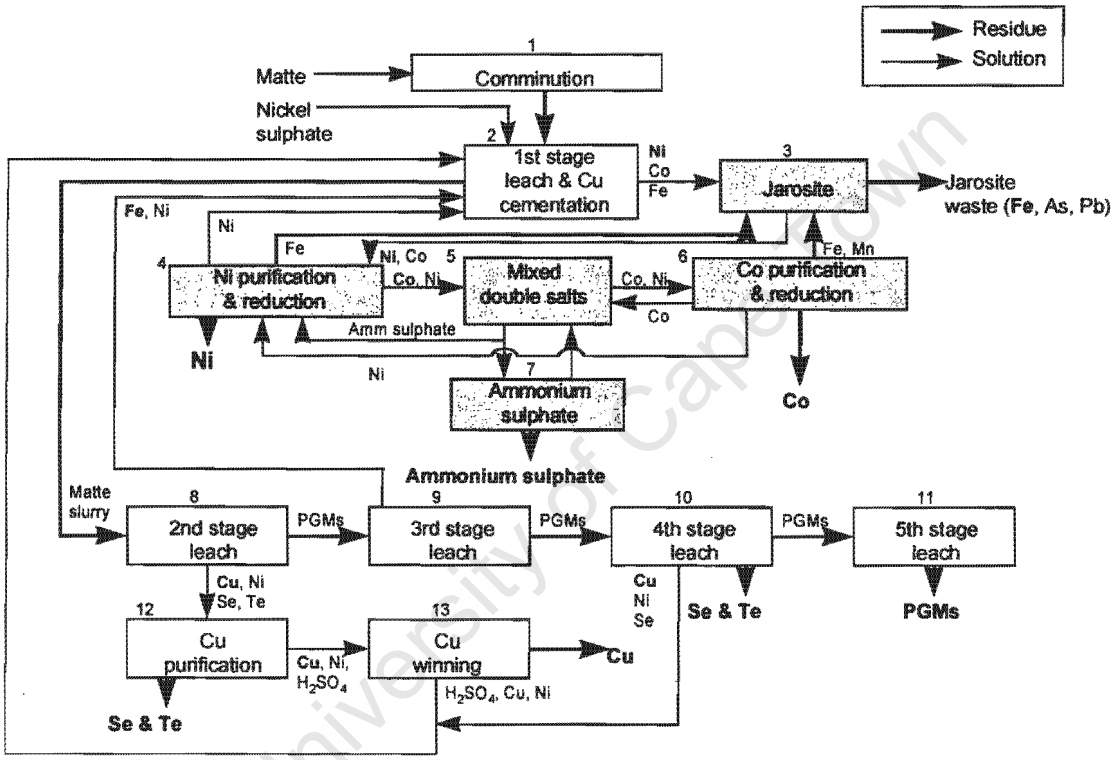


Figure 7.1: Unit operations relevant to nickel sulphate processing, as shown with shading.

The contribution of nickel sulphate to the elemental inputs, as extracted from the overall average mass balance (Appendix 3), is given in Table 7.1.

ELEMENT	% CONTRIBUTION FROM NICKEL SULPHATE
Ni	19.8
Cu	0.02
Co	14.1
Fe	22.6
S	16.4

Table 7.1: The contribution of nickel sulphate to the total elemental inputs.

The values given in Table 7.1 were used to calculate the contribution of nickel sulphate to the reagent consumptions incurred in each of the unit operations based on the process chemistry (section 2.4) and the reagent flowrates as shown in the elemental mass balance (Appendix 3), converted to t/month (a 30 day month). Only those reagents which were included in the LCA were considered, and outputs which did not incur environmental impacts were excluded (such as those which were classed as open loop outputs). The resultant inputs and outputs are presented in Table 7.2.

22.6% of the reagents (oxygen and ammonia) used in the jarosite process was ascribed to the processing of nickel sulphate, based on the contribution of this material to the iron input (refer to Table 7.1). Similarly, 19.8% of the reagents used in the nickel purification and reduction operations (ammonia, nitric acid, and hydrogen) were attributed to nickel sulphate, as nickel is the primary component of these process streams. 79% of the total ammonia and sulphuric acid used in the mixed double salts process was due to consumption by nickel in the input streams, while cobalt consumed the remainder. This was based on the ratio of nickel to cobalt in the input streams, as nickel and cobalt react in the same manner during this stage of processing. 19.8% of the portion assigned to nickel and 14% of that assigned to cobalt was then attributed to nickel sulphate.

14% of the oxygen and hydrogen used for cobalt purification and reduction respectively, were due to the contribution of nickel sulphate to cobalt production. The sulphuric acid consumption is attributed to Ni (19.8% due to nickel sulphate), as this reagent is used to precipitate the nickel double salt in order to separate the Ni

from the Co. The ammonia consumed during cobalt purification is divided equally between Ni and Co as a first approximation, as it is used to dissolve both the mixed double salts (a similar quantity of nickel and cobalt is present in the MDS cake), and then ammonia is used in the oxidation reaction of cobalt to cobaltic pentammine (reaction 31, section 2.4.3). Ammonia is also used later to neutralise free acid thereby re-dissolving the nickel mixed double salt. The relative contributions of nickel sulphate to the nickel and cobalt input were then applied to these allocated reagent consumptions. No reagents are added to the ammonium sulphate circuit, thus no allocation was necessary.

The quantity of steam used per ton of nickel produced from nickel sulphate would be approximately the same as that from matte, as the majority of the steam is used in the nickel reduction and ammonium sulphate circuits. The LCI data for the boilers was thus allocated according to the ratio of nickel produced from each raw material (19.8% of the nickel produced was derived from the nickel sulphate input). Similarly, 19.8% of the total hydrogen and carbon dioxide inputs to the BMR were due to the reduction of nickel from nickel sulphate (the majority of hydrogen is consumed by the nickel reduction circuit (refer to the elemental mass balance in Appendix 3), and a significant portion of the carbon dioxide is used to purge the autoclaves prior to reduction). The LCI hydrogen generation data was thus adjusted accordingly. The nitrogen gas is primarily used to purge hydrogen gas line lines, thus 19.8% of the N_2 input in the base case was also attributed to nickel sulphate. (This approximation excludes the use of nitrogen to purge cobalt reduction autoclaves, as a relatively small quantity of Co is produced each month).

The total water consumption by those unit operations which were not relevant to nickel sulphate processing (refer to Table 4.10) was subtracted from the total BMR water input. The ratio of Ni produced from nickel sulphate to total nickel produced was then applied to this to calculate the contribution due to nickel sulphate processing. The contribution by nickel sulphate to the elemental inputs (Table 7.1) was used to calculate the contributions of this raw material to the effluent impurities. For the base case, 14.5% of the ammonia input reported to the effluent, thus this percentage was applied to the ammonia usage due to nickel sulphate processing in the effluent calculation.

STREAM	t/mth	t/t Ni produced
BMR PROCESS INPUTS		
Raw materials: Ni sulphate	1124	5.9
Liquid reagents: H_2SO_4	71.3	0.37
HNO_3	12	0.06
Ammonia	168.4	0.88
Gaseous reagents: Oxygen	1.1	$5.7x10^{-3}$
Nitrogen	110	0.57
Inter-unit flows: Steam	6516	34
Hydrogen used	14	0.07
CO_2 used	31	0.16
Standard flows: Water	5623	29
OUTPUTS: Ni produced	191.4	1.0
Effluent: Ni (waterborne)	1.1	$5.7x10^{-3}$
Co (waterborne)	0.06	$3.1x10^{-4}$
Nitrogenous compounds (waterborne)	24.4	0.13
Sulphates (waterborne)	14.9	0.08
STEAM GENERATION INPUTS: Coal	1071	5.6
Oxygen (from air)	2342	12
Boiler feed water	7969	42
Water to ash	81	0.42
OUTPUTS: Ash (dry)	154	0.80
H_2O in ash	81	0.42
SO_2	7.5	0.04
CO_2	2750	14
H_2O vapour	458	2.4
NO_2	44	0.23
Effluent	148	0.77
Steam to PMR	375	2.0
Steam to H_2	909	4.7
Steam to BMR	6516	34
Thus steam loss at boilers	20.5	0.11
H_2 GENERATION INPUTS: Natural gas (feed)	60.8	0.32
Steam (incl. heating)	909	4.7
Inputs for heating: Natural gas (fuel)	58.8	0.31
Oxygen (from air)	125	0.65
OUTPUTS: Steam loss	851	4.4
H_2 PMR	0.2	$1.0x10^{-3}$
H_2 vented	1.8	$9.4x10^{-3}$
H_2 BMR	14	0.07
CO_2 BMR	31	0.16
CO_2 vented	71.7	0.37
Outputs ex heating: CO_2	99.2	0.52
H_2O vapour	79.4	0.41
N_2	5.3	0.03
ELECTRICITY (kWh/mth or kWh/t Ni produced)	736955	3850

Table 7.2: Estimated inputs and outputs due to nickel sulphate processing, as derived from the base case.

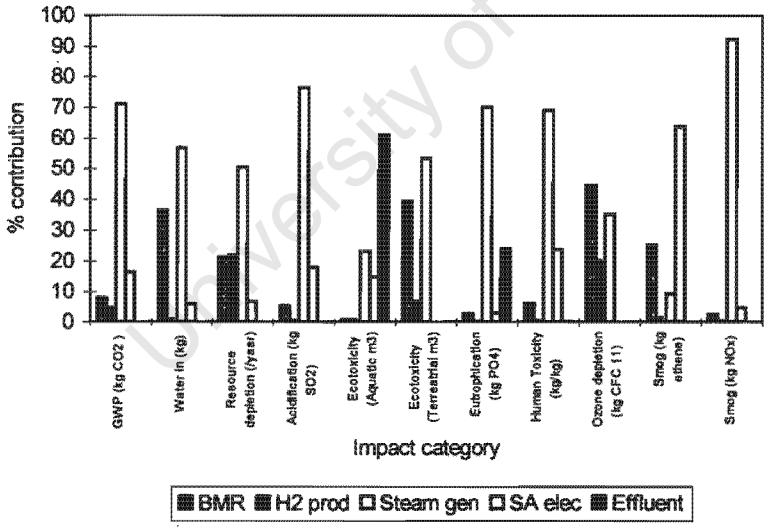
The total electricity consumption was decreased to include only the utilities, Ni handling and reduction, Co circuits, and ammonium sulphate consumptions (refer to Table 4.4). 736955kWh/mth of the electricity was then ascribed to nickel sulphate (3721353kWh/mth / 966.5tNi (total production) * 191.4t Ni (ex Ni sulphate)).

7.3) EVALUATION

7.3.1) Environmental profiles

The environmental profile for nickel sulphate was obtained by entering the input and output data as given in Table 7.2 into the PEMS software. Mass balance closure was obtained by ascribing the difference between the inputs and outputs to Open Loop Outputs, as was consistent with the base case. The environmental profile is presented in Table 7.3, while the percentage contributions of the various processes to the total environmental profile is shown in Figure 7.2.

Figure 7.2: Percentage contributions of processes to the environmental profile for nickel production from nickel sulphate



The environmental profile for the processing of the remainder of the raw material as per the base case (primarily Impala matte, plus a small quantity of cobalt nitrate and toll refining matte), was similarly obtained using the difference between the inputs and outputs for the overall base case and those given in Table 7.2. The environmental profile is presented in Table 7.4. Figure 7.3 compares the environmental profiles for the base case to that of nickel sulphate and matte processing (the latter also includes a small quantity of cobalt nitrate).

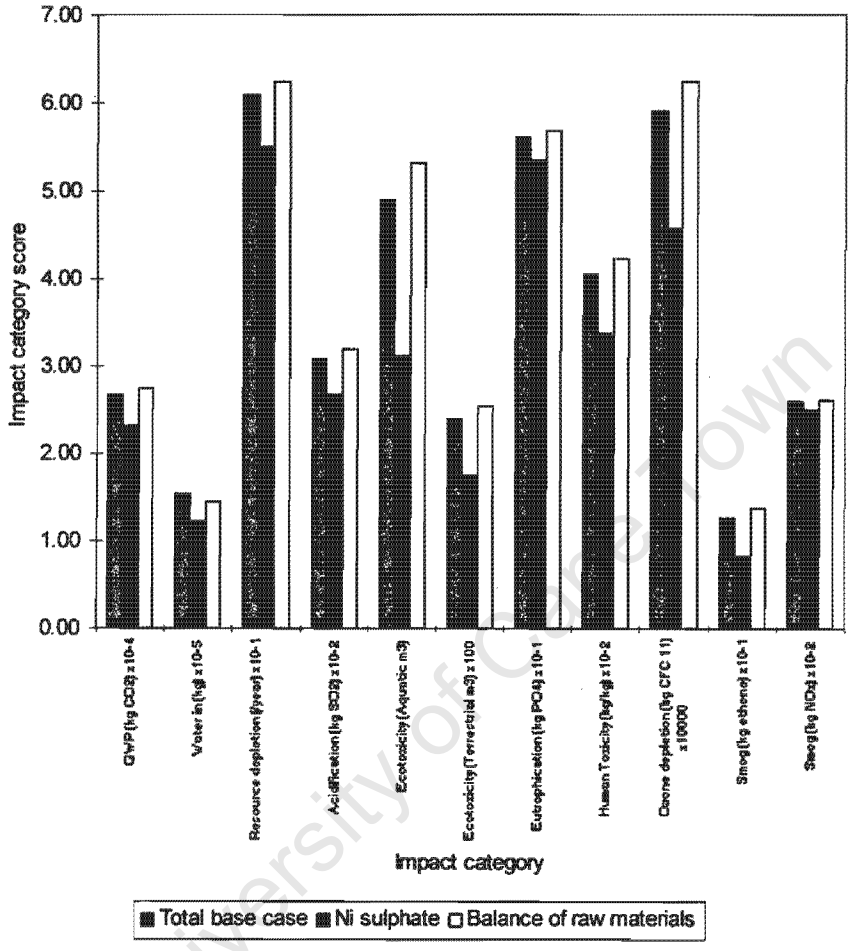
Impact category	TOTAL	BMR total	BMR process	O_2 from air decomposition	N_2 from air decomposition	H_2SO_4	HNO_3	Ammonia	H_2 total	H_2 produced	Natural gas delivered UK	Steam total	Steam generated	Coal, hard UK	SA elec	Effluent
GWP (kg CO_2)	**23119**	**1848**	0.00	1.67	167	92.6	38.5	1548	**1063**	893	170	**16444**	14368	2076	**3764**	**0.00**
Water in (kg)	**121832**	**44088**	29378	73.9	7391	2124	147	4973	**923**	0.00	923	**69767**	42059	27708	**7055**	**0.00**
Resource depletion (/year)	**55.0**	**11.7**	0.00	0.01	0.59	0.44	0.25	10.4	**12.0**	0.00	12.0	**27.7**	0.00	27.7	**3.63**	**0.00**
Acidification (kg SO_2)	**266**	**14.0**	0.00	0.01	1.05	2.35	0.27	10.3	**0.96**	0.00	0.96	**204**	200	3.84	**47.3**	**0.00**
Ecotoxicity (Aquatic m^3)	**3.10**	**0.02**	0.00	4.69E-05	0.00	0.00	0.00	0.01	**0.02**	0.00	0.02	**0.72**	0.00	0.72	**0.45**	**1.90**
Ecotoxicity (Terrestrial m^3)	**1.74E-02**	**6.85E-03**	0.00E+00	1.83E-05	1.83E-03	1.03E-03	1.41E-04	3.83E-03	**1.21E-03**	0.00E+00	1.21E-03	**9.30E-03**	0.00E+00	9.30E-03	**5.18E-07**	**0.00E+00**
Eutrophication (kg PO_4)	**53.5**	**1.50**	0.00	0.00	0.05	0.02	0.04	1.39	**0.09**	0.00	0.09	**37.6**	29.9	7.76	**1.56**	**12.7**
Human Toxicity (kg/kg)	**337**	**21.3**	0.00	0.02	1.55	2.93	0.40	16.4	**1.62**	0.00	1.62	**233**	226	6.44	**80.0**	**0.95**
Ozone depletion (kg CFC 11)	**4.57E-04**	**2.04E-04**	0.00E+00	3.90E-07	3.90E-05	1.69E-05	3.57E-06	1.44E-04	**9.17E-05**	0.00E+00	9.17E-05	**1.61E-04**	0.00E+00	1.61E-04	**0.00E+00**	**0.00E+00**
Smog (kg ethene)	**8.36**	**2.11**	0.00	0.00	0.04	0.02	0.04	2.01	**0.13**	0.00	0.13	**0.78**	0.00	0.78	**5.35**	**0.00**
Smog (kg NO_x)	**251**	**6.36**	0.00	0.00	0.33	0.17	0.19	5.67	**0.59**	0.00	0.59	**232**	230	2.02	**11.9**	**0.00**

Table 7.3: Environmental profile for the production of one ton of nickel from nickel sulphate, as derived from the base case.

Impact category	TOTAL	BMR total	BMR process	O_2 from air decomposition	N_2 from air decomposition	H_2SO_4	HNO_3	Ammonia	H_2 total	H_2 produced	Natural gas delivered UK	Steam total	Steam generated	Coal, hard UK	SA elec	Effluent
GWP (kg CO_2)	**27478**	**2742**	0.00	441	168	337	39	1758	**1063**	893	170	**16446**	14368	2077	**7226**	**0.00**
Water in (kg)	**143747**	**59484**	19053	19494	7417	7724	148	5648	**923**	0.00	923	**69797**	42071	27726	**13544**	**0.00**
Resource depletion (/year)	**62.4**	**15.8**	0.00	1.54	0.59	1.59	0.25	11.8	**12.0**	0.00	12.0	**27.7**	0.00	27.7	**6.97**	**0.00**
Acidification (kg SO_2)	**318**	**24.3**	0.00	2.77	1.05	8.53	0.28	11.7	**0.96**	0.00	0.96	**202**	198	3.84	**90.8**	**0.00**
Ecotoxicity (Aquatic m^3)	**5.32**	**0.04**	0.00	0.01	0.005	0.01	0.00	0.01	**0.02**	0.00	0.02	**0.72**	0.00	0.72	**0.87**	**3.68**
Ecotoxicity (Terrestrial m^3)	**2.54E-02**	**1.49E-02**	0.00E+00	4.82E-03	1.83E-03	3.76E-03	1.43E-04	4.35E-03	**1.21E-03**	0.00E+00	1.21E-03	**9.30E-03**	0.00E+00	9.30E-03	**9.95E-07**	**0.00E+00**
Eutrophication (kg PO_4)	**56.8**	**1.87**	0.00	0.13	0.05	0.08	0.04	1.58	**0.09**	0.00	0.09	**37.3**	29.5	7.8	**3.00**	**14.5**
Human Toxicity (kg/kg)	**423**	**35.4**	0.00	4.10	1.56	10.6	0.40	18.7	**1.62**	0.00	1.62	**231**	224	6.44	**154**	**1.32**
Ozone depletion (kg CFC 11)	**6.24E-04**	**3.71E-04**	0.00E+00	1.03E-04	3.91E-05	6.16E-05	3.60E-06	1.63E-04	**9.18E-05**	0.00E+00	9.18E-05	**1.61E-04**	0.00E+00	1.61E-04	**0.00E+00**	**0.00E+00**
Smog (kg ethene)	**13.7**	**2.53**	0.00	0.10	0.04	0.07	0.04	2.28	**0.13**	0.00	0.13	**0.78**	0.00	0.78	**10.3**	**0.00**
Smog (kg NO_x)	**261**	**8.45**	0.00	0.88	0.34	0.61	0.19	6.44	**0.59**	0.00	0.59	**229**	227	2.02	**22.8**	**0.00**

Table 7.4: Environmental profile for the production of one ton of nickel from the remainder of the raw materials (Impala matte, plus a small quantity of cobalt nitrate and toll refining matte), as derived from the base case.

Figure 7.3: Comparison of the overall environmental profiles per ton of nickel produced for the base case, the processing of nickel sulphate, and the processing of the remainder of the raw materials



7.3.2) Discussion

Although the system boundaries had changed from the base case for this scenario, because nickel sulphate processing was assessed as a separate entity from the processing of matte and cobalt nitrate material, this case study allowed for a comparison of the potential impacts associated with each of these process operations in isolation.

The generation of steam was also the main contributor to the majority of the impact category scores for the production of nickel from nickel sulphate, as can be seen from Figure 7.2. This is because the steam required per ton of nickel produced remained the same. The trends in the contributions of the various processes to the overall scores was similar to the base case (refer to Figure 5.1).

It is evident from Figure 7.3 that the environmental impacts per ton of nickel produced from nickel sulphate were lower for every impact category than those for the processing of matte plus cobalt nitrate. (The impact scores were also obviously lower than for the overall base case which included the processing of matte, nickel sulphate, and cobalt nitrate). The main contributor to this was the decreased electricity requirement per ton of nickel produced. In addition there was a lower oxygen, sulphuric acid, and ammonia requirement per ton of nickel produced for the BMR process. These both resulted from the fact that comminution, leaching, and copper purification and electrowinning were not required for nickel sulphate processing. The toxicity and eutrophication scores (per ton of nickel produced) from the effluent were also lower for the nickel sulphate case, due to the composition of this raw material, and the decreased ammonia and sulphuric acid requirements per ton of nickel produced (which would presumably result in lower nitrogenous and sulphate impurity levels in the effluent).

The processing of matte (plus cobalt nitrate) had the highest impact scores in all categories except water usage, which was merely due to the exclusion of rainwater input into the effluent stream (refer to both Table 7.3 and 7.4). The tonnage of nickel produced from nickel sulphate multiplied by the relevant impact scores for the processing of this material, plus the tonnage of nickel produced from matte multiplied by the impact scores for the processing of matte (plus cobalt nitrate), gives the total environmental impact scores for the base case. When these values are divided by the total nickel production, the overall base case unit environmental scores are obtained. Due to the larger contribution of matte processing to nickel production, it contributed more to the overall impact scores than nickel sulphate processing, as can be seen from Figure 7.3.

It may thus be concluded that the environmental impact scores should decrease with an increasing share of nickel sulphate in the raw materials. This could not be seen from the collated monthly data, however, due to the lower contribution of nickel sulphate to the nickel production. This is shown in Figures 7.4 and 7.5, where the greenhouse effect and resource depletion impact categories from the base case monthly environmental profiles are used as examples. The impact scores are plotted as a function of the percentage nickel sulphate in the raw material inputs. Even with a nickel sulphate input of 50% by mass, the matte still

contributes approximately 70% of the nickel input (and thus nickel production), as the matte contains around 50% Ni, while the nickel sulphate contains approximately 20% Ni.

Figure 7.4: The relationship between the greenhouse effect impact category and the percentage nickel sulphate processed

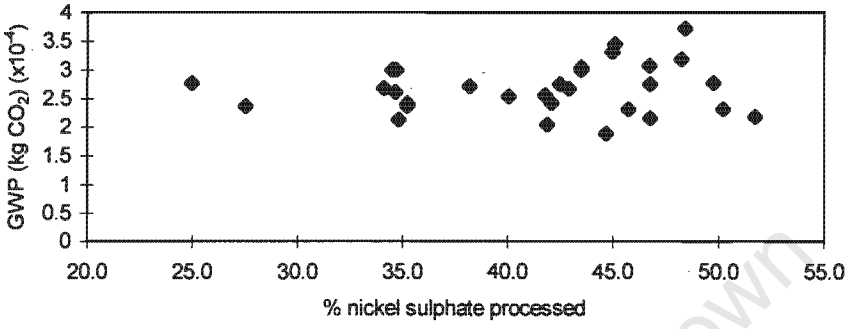
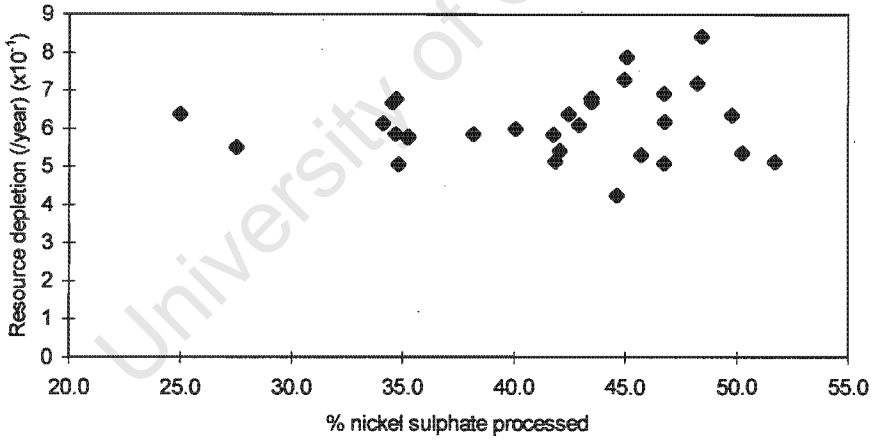


Figure 7.5: The relationship between the resource depletion impact category and the percentage nickel sulphate processed



7.4) CONCLUSION

The environmental profile obtained for the processing of nickel sulphate alone indicated that the potential environmental impacts per ton of nickel produced were lower than for the processing of matte (plus cobalt nitrate). This was due to the properties of this raw material, as it does not require milling or leaching, as well as its composition, which eliminates the need for copper purification and electrowinning.

Although the processing of nickel sulphate results in lower impact scores, within the definition of this study, than the treatment of matte, it would not be feasible to treat this material alone for economic reasons (the PGMs present in the matte are the primary sources of income for Impala Platinum Ltd). The BMR process design may also not be suitable for this. However, the analysis presented in this chapter indicates that the processing of nickel sulphate does not impair the environmental performance of the BMR.

It must be remembered that all of the potential impacts were allocated to nickel in the case of matte processing, which would have introduced a degree of bias into the results. A further study which includes the production of matte and nickel sulphate would also present a more complete comparison.

Chapter 8: SCENARIO B: INCREASED COBALT PRODUCTION AND THE CONSEQUENT INTRODUCTION OF COBALT SOLVENT EXTRACTION TECHNOLOGY

8.1) INTRODUCTION

The first patent describing the use of an organic acid (oxalic acid) to extract nickel from a solution was filed in 1902 by T. Jenkins, while the first patent on the use of solvent extraction (SX) to separate nickel from cobalt was disclosed in 1934 (Jacobs *et al*, 1985). Cobalt/nickel SX separations from sulphate solutions obtained by acid leaching has been practised commercially for over ten years (Flett, 1997; Bautista, 1993; and Xun *et al*, 1987).

Cyanex 272 manufactured by Cytec Industries, is one of the most commonly used extractants (it is used, for example, at Outokumpu Oy at Harjavalta, Finland (Knuutila *et al*, 1997)), although di-2-ethylhexyl phosphoric acid (DEHPA) is used by Rustenburg Base Metals Refinery (refer to section 2.2). The chemical composition of Cyanex 272 is bis(2,4,4-trimethylpentyl)phosphinic acid, as shown in Figure 8.1, and it extracts metals via a cation exchange mechanism, involving the release of a proton from the phosphinic acid functional group (Cytec Industries, 1996). Selective extraction is obtained by pH control. Cyanex 272 is known to provide larger separation factors than DEHPA or phosphonic acid extractants (Rickelton *et al*, 1984). Indeed, under comparable conditions, cobalt-nickel separation efficiencies increase in the order phosphoric<phosphonic<phosphinic acids (Preston, 1982).

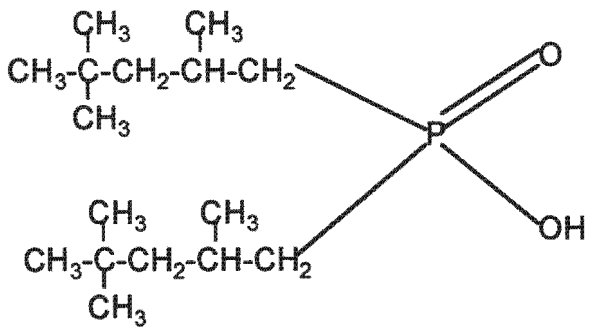


Figure 8.1: Chemical structure of Cyanex 272.

For Ni/Co SX, the extractant is suspended in a diluent (usually a n-paraffin), and an antioxidant (commonly BHT: 2,6-bis(1,1-dimethylethyl)-4-methyl phenol) is added. This is necessary to prevent the oxidative degradation of the diluent to carboxylic acids, which is catalysed by cobalt. An aliphatic diluent is employed, as degradation is most severe in highly aromatic diluents and at high temperatures (Feather *et al*, 1996). The use of solvent extraction in circuits incorporating hydrogen reduction stages, such as that of Impala's BMR, prescribes the incorporation of efficient organic removal steps prior to reduction. Failure to remove entrained organic results in an alteration of the surface morphology of the nickel powder, inhibiting briquette formation. The number of nickel densifications per cycle may also be limited (refer to section 2.4) (Fox *et al*, 1998).

The processing of primarily Impala matte, as is the current situation at Impala's BMR, does not warrant the introduction of a cobalt SX circuit, due to the low cobalt through-put. However, the possibility of toll refining a mixed Ni/Co sulphide intermediate product from the Far East was explored by Impala during 1996 and 1997. In addition to doubling the current BMR throughput (Fox *et al*, 1998), a significant increase in cobalt production would have resulted from this contract, which however did not materialise. As similar material may be toll refined in future, the case study presented here should prove valuable in assessing the environmental impacts associated with processing this type of material, and the process technology changes associated with it.

A feasibility study was undertaken during the project planning stages, in conjunction with Bateman (South Africa) to evaluate the processing of Far East Mixed Sulphide (FEMS) material. The proposed process included a cobalt SX circuit in order to enhance cobalt recoveries, as approximately 25% of the cobalt input is currently lost either to the nickel or the ammonium sulphate products (Fox *et al*, 1998). The current process was also incapable of processing the increased Co through-put.

8.2) PROCESS DESIGN

The FEMS material, which had been sourced for toll refining by Impala Platinum, did not contain precious metals. It was therefore decided to separate the processing of this material from the Impala matte, in order to prevent dilution and contamination of the PGM concentrate. The sulphidic nature of the material also required a higher

pressure and temperature leach than that currently employed in the autoclaves used for matte leaching. Specialised equipment was therefore required. For these reasons, it was decided that the FEMS material was to be leached separately, and would only be combined with the present Ni/Co stream post jarosite, at which stage Co SX would be employed. The proposed flowsheet is depicted in Figure 8.2.

A milling stage was to be incorporated in order to break up any large lumps of material which had formed in transit, due to moisture entrained in this fine precipitate. The material would then be slurried with demineralised water and recycled process water, before passing into a pressure leach autoclave, along with sulphuric acid and the nickel and cobalt reduction end solution sulphide precipitate. The following exothermic reactions would occur during the leach (Walker *et al*, 1996):

$$xS + 2O_2 \rightarrow xSO_4$$

where x is Ni, Co, Cu, Fe or Zn.

More specifically,

$$8NiS + 2H_2SO_4 + O_2 \rightarrow 2NiSO_4 + 2Ni_3S_4 + 2H_2O$$

$$2Ni_3S_4 + 2H_2O + 15O_2 \rightarrow 6NiSO_4 + 2H_2SO_4$$

The autoclave discharge would then be filtered (with the aid of pre-coat powder). The solid residue would consist primarily of gangue oxides, and would be routed to Impala's smelter in Rustenburg. The filtrate would be an aqueous solution of nickel and cobalt sulphate, with small amounts of copper, zinc, iron, cadmium, manganese and sulphuric acid impurities.

The copper would then be removed via cementation with sodium hydrogen sulphide (NaHS) and Western Mining Corporation (WMC) matte leach liquor. (The WMC matte would be milled and acid leached in a separate circuit, and the solid leach residue would be added to the FEMS leach operation). Some of the zinc and cadmium would also be precipitated in this stage:

$$ySO_4 + NaHS \rightarrow yS + NaHSO_4$$

where y is Cu, Zn or Cd.

Sulphuric acid would be neutralised by the addition of anhydrous ammonia. The residue obtained upon filtration (again utilising pre-coat powder), would either be routed to the smelter or sent out for toll refining (to a zinc refiner, for example).

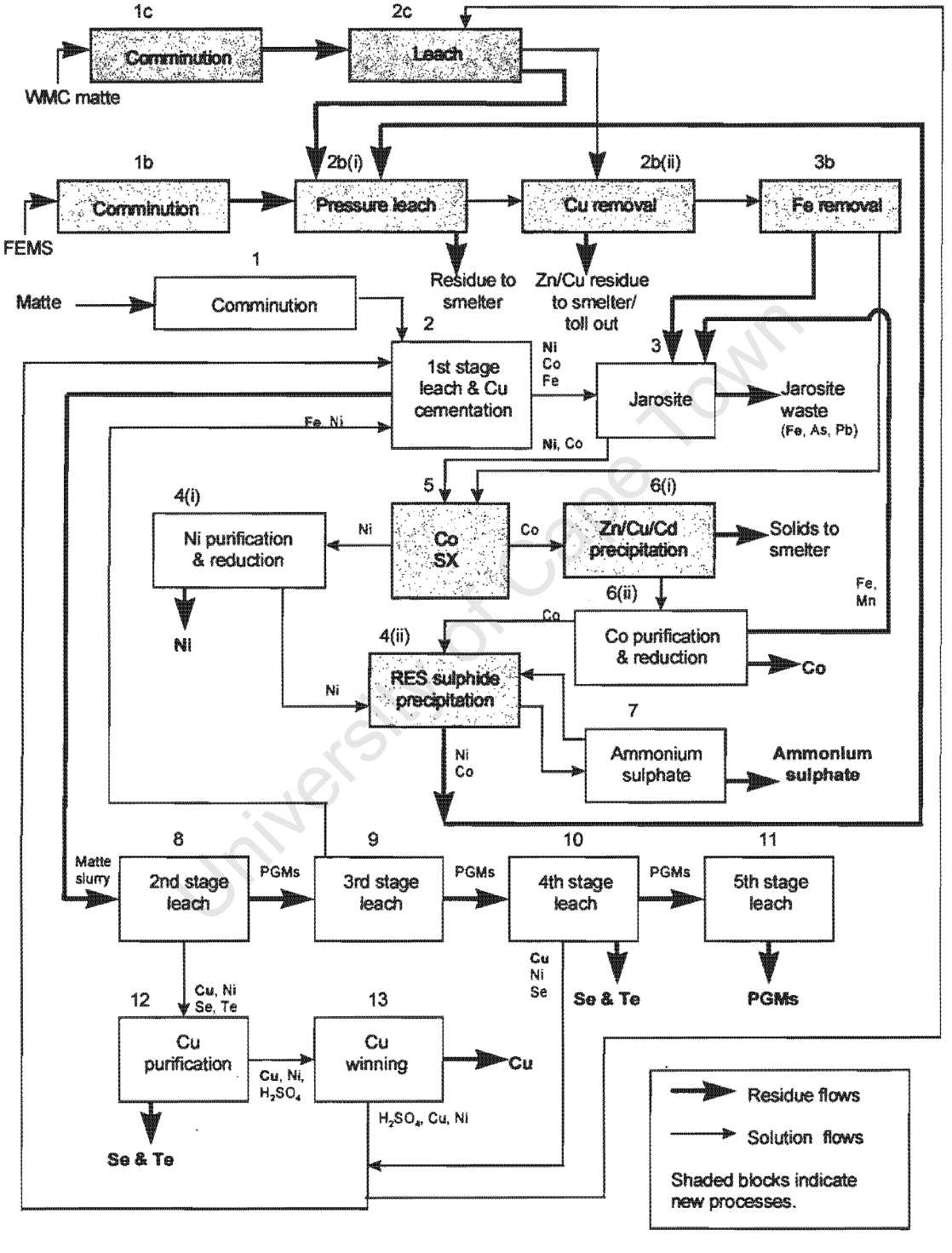


Figure 8.2: Base Metal Refinery flowsheet for FEMS processing, incorporating cobalt solvent extraction

Iron would then be removed from the filtrate. Three options were available for achieving this. Firstly, the iron could be precipitated as jarosite, as is performed currently. This was deemed nonviable, however, as the current jarosite circuit does not have the extra capacity required to process this entire volume of material, and it would be too expensive to install a new separate jarosite facility to treat it. Similarly, a solvent extraction process to effect removal of zinc and iron, pre-Co SX was considered to be uneconomical. A goethite iron precipitation stage was therefore decided upon, as it was the most cost-effective option in light of the fact that the capital equipment required was already available in the current plant and thus would not have to be purchased (Ralph, 1998).

In this process, ammonium hydroxide and air are used to precipitate the iron. A portion of the nickel and cobalt may be simultaneously precipitated as hydroxides, however, thus effective washing of the cake is necessary to remove these entrained metals.

$$12FeSO_4 + 2H_2O + 3O_2 \rightarrow 4FeOOH + 4Fe_2(SO_4)_3$$

$$Fe_2(SO_4)_3 + 6NH_4OH \rightarrow 2Fe(OH)_3 + 3(NH_4)_2SO_4$$

The goethite precipitate would be re-pulped and routed to the existing jarosite circuit, in order to be re-precipitated as jarosite, which would then be co-disposed to landfill with that jarosite currently produced. Any Ni and Co remaining in the goethite post washing would be recovered during this re-precipitation process.

The filtrate from the goethite precipitation would then join the jarosite filtrate at the cobalt solvent extraction circuit. After passing through a polishing filter and a heat exchanger (to reduce the temperature of the feed to below 50°C to prevent oxidation of the organic diluent), the feed solution would be mixed with the solvent mixture in mixer-settler units. The solvent mixture would consist of a 10% solution of Cyanex 272 in a n-paraffin diluent containing ½ to 1% BHT (the diluent and anti-oxidant was to be supplied pre-mixed by Sasol). Ammonium hydroxide would be employed to maintain the pH at approximately pH6. The raffinate, containing nickel sulphate, would then be separated from the organic by gravitation. After removal of any residual organic present (assisted by carbon filter columns), the solution would enter the current nickel purification and reduction circuit.

The loaded organic containing the cobalt would then be scrubbed with recycled cobalt sulphate solution, in order to displace any nickel present. The scrubbed organic would subsequently be stripped with dilute sulphuric acid. Any remaining entrained organic would be removed from the cobalt sulphate solution thus produced. Due to the presence of traces of Cu, Zn and Cd impurities in this solution, a pH adjustment (utilising anhydrous ammonia), followed by a sulphide precipitation stage (via NaHS addition) would be necessary. The residue thus produced would be sent to the smelter, and the filtrate would enter the existing Co purification circuit.

The nickel and cobalt reduction end solutions would be combined with an ammonium sulphate purge stream, and treated with NaHS to precipitate residual nickel and cobalt. The residue would be recycled to the FEMS pressure leach circuit. The filtrate would continue to the existing ammonium sulphate plant.

8.3) GOAL DEFINITION AND SCOPING

The cradle to gate LCA relating to the processing of FEMS material by means of Co SX is to be compared to the base case, in order to evaluate the consequent change in environmental performance of the BMR as a whole. Thus the goal definition and scoping exercise for this scenario was based on that presented in Chapter 3.

The boundary diagram for the FEMS processing/Co SX case is given in Figure 8.3, which also indicates the inputs and outputs to each unit operation. The FEMS material and the WMC matte were taken as open loop inputs, as is consistent with the base case LCA boundary. Similarly, the residues which would be generated from the FEMS material were classified as open loop outputs, as they would be returned to Mineral Processes.

The transport of the FEMS material to the BMR site was excluded from the study, which is consistent with the base case in which transport of Impala matte and other feed materials was excluded. This exclusion also aids in the application of this case study to the processing of similar material from other sources. The transport of the FEMS material was later included by means of a sensitivity analysis, in order to quantify the potential contribution of transport of this material to the environmental

profile. Capital and maintenance requirements were excluded, as was packaging of the products, according to the system boundaries defined in section 3.3.1.

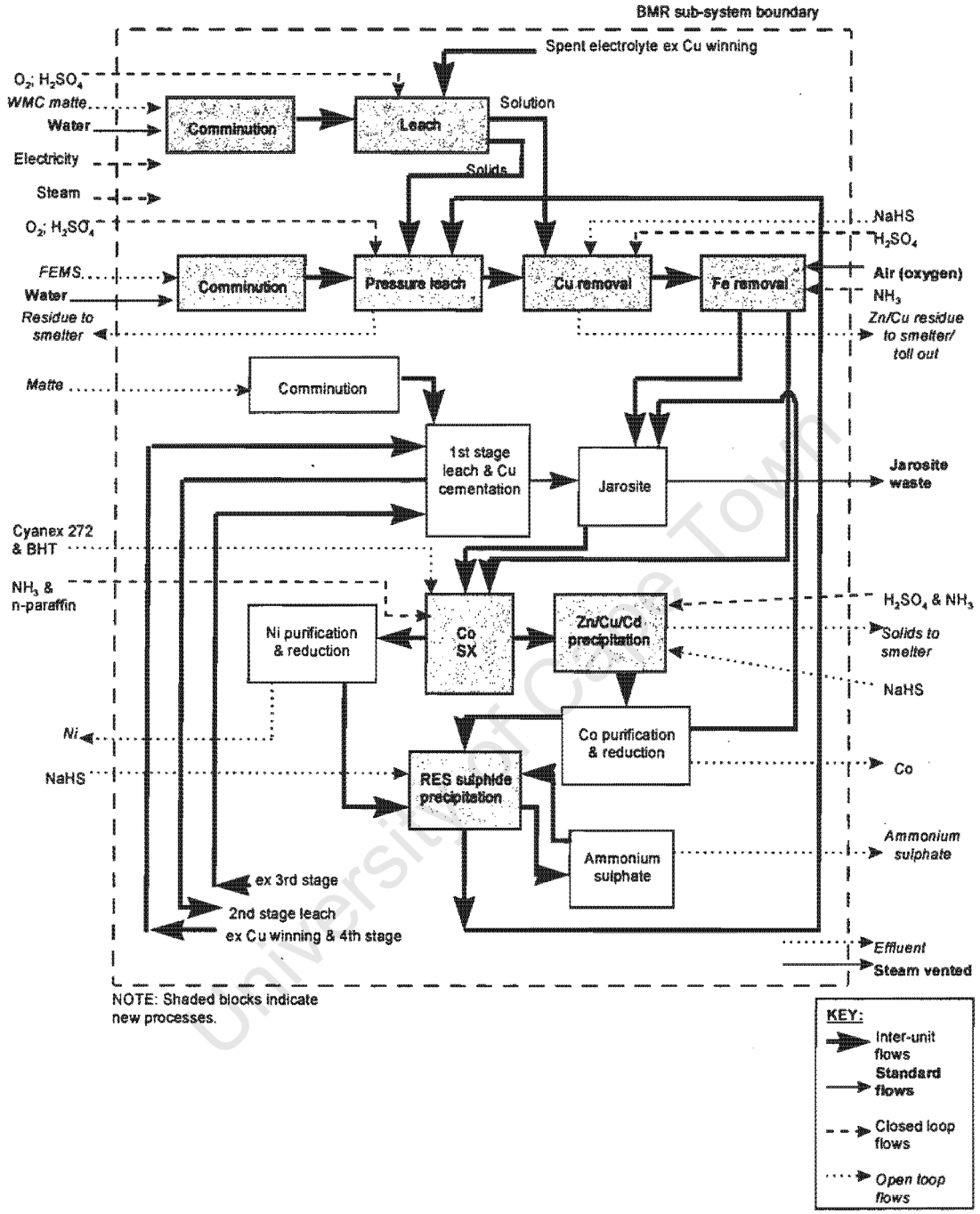


Figure 8.3: Base Metal Refinery sub-system boundary for FEMS processing, incorporating cobalt solvent extraction, and indicating additional reagent requirements.

(Note: Processes from 2nd stage onwards are excluded from this figure for simplicity only but they are included in the LCA).

8.4) DATA COLLECTION AND LCI

The plant design in the pre-feasibility study was based on the processing of Impala matte, all material currently being toll refined, as well as approximately 300 tons per month of Western Mining matte, and 1200 tons per month of Far East Mixed Sulphides. The additional output would be approximately 830t of Ni, 35t of Co, and 1t of Cu per month.

The changes in reagent and utilities consumption that would consequently occur were calculated as part of an operating cost estimate in the pre-feasibility study (Walker *et al*, 1996). The error in these estimates was less than 10%. The calculations were based upon the process design as given in Figure 8.2 and 8.3, and upon stoichiometric amounts derived from the mass balance generated in-house utilising Metsim (Impala Nickel Business Development Unit, 1996). Other consumptions which are not included in Metsim (such as those used by the BMR utilities operations) were calculated from historical Impala operating data.

The compositions of the FEMS material and the WMC matte are given in Table 8.1.

ELEMENT	% COMPOSITION: FEMS MATERIAL	% COMPOSITION: WMC MATTE
Ni	51	72
Co	2.9	1.1
Cu	0.008	0.3
Fe	0.1	0.7
Zn	0.7	-
S	30	21

Table 8.1: Average analytical composition of FEMS material and WMC matte.

The inputs and outputs for the FEMS processing by SX option (which includes current process volumes, as given in the base case in Table 4.2), are presented in Table 8.2. The new or changed entries are shown in bold, and the sources of the new data are included. It was determined during the pre-feasibility study that there was sufficient capacity for the new process requirements in the current utility

operations (provision of hydrogen, demin water, steam, compressed air etc). It is evident from Table 8.2 that the reagent inputs increased, with the exception of sulphuric acid consumption, which decreased due to the increased sulphur input from the raw materials.

The percentage Ni, Cu and Co recoveries to product as indicated in Table 8.2, were obtained from the FEMS Metsim balance. The steam generation process was assumed to be linear to allow for the scaling up of some of the inputs and outputs. The hydrogen plant calculations were based on the hydrogen gas requirements. The steam vented from the BMR process was calculated from the average percentage steam loss in the base case. The total additional water consumption was taken from the pre-feasibility study. The additional water requirements relating to the boiler (boiler feed water (10550kℓ) and water for ash (108kℓ)) were subtracted from this, as was the increased condensate returns (1318kℓ; the ratio of condensate returns to steam usage by the BMR for the base case was applied to the new steam value, as it was assumed that the percentage condensate returns would remain approximately the same). In this manner the BMR water consumption was derived.

The additional ammonium sulphate and jarosite produced were calculated from the percentage of sulphur and iron inputs reporting to these products, respectively, as given in the FEMS Metsim balance. The additional S and Fe inputs from the FEMS material and the WMC matte were multiplied by these percentages, and then converted to the increase in by-product mass, according to the percentage composition of S and Fe in them (as given in the FEMS Metsim balance).

In terms of the effluent composition, it was assumed that the new effluent stream arising from the BMR process would be of a similar quality (in terms of Ni and Cu concentration) to that in the base case. Although considerably more of these metals would be processed per month, the new process would be more automated than the current one, which would reduce the possibility of effluent contamination due to operator error. The quantities of Ni and Co to Ergo as in the base case were adjusted according to the increased effluent volume arising from the BMR process (it was assumed that the BMR process was the major source of these ions in the effluent). Ni and Co losses to Ergo were thus estimated at 6.2t/mth and 0.5t/mth, respectively. The copper losses (in t/mth) were taken as that of the base case, as the Cu input and circuit did not change.

AVERAGE BMR PROCESS DATA:

INPUTS	t/mth	SOURCE
Raw materials		
Impala matte	1343	Ex month end reports
Other toll refining material	152	Ex metal accounting
Ni sulphate	1124	Ex metal accounting
Co nitrate	118	Ex metal accounting
FEMS	1176	Ex FEMS Metsim balance
WMC matte	318	Ex FEMS Metsim balance
Liquid reagents		
H_2SO_4	954	Ex FEMS pre-feasibility study
HNO_3	113	Factored up for inc Ni prod
Ammonia	1589	Ex FEMS pre-feasibility study
Gaseous reagents		
Oxygen	2249	Ex FEMS pre-feasibility study
N_2	1484	Ex FEMS pre-feasibility study
Inter-unit flows		
Steam	37687	Ex FEMS pre-feasibility study
Hydrogen used	159	Ex FEMS pre-feasibility study
CO_2 used	321	Ex H_2 balance
Standard flows		
Water	23098	Ex feas. -H_2O for extra steam etc
TOTAL INPUTS	71885	t
OUTPUTS		
Main product		
Ni produced	1792.5	99.7% recovery of extra Ni in
By-products		
Cu cathode	413	99.4% recovery of extra Cu in
Co powder	42.9	99.1% recovery of extra Co in
Ammonium sulphate	4217	98.9% of extra S to $AmSO_4$
Se/Te solids	2.88	Ex Commercial Department
PGM concentrate	2.84	Ex metal accounting
PGM solution	29.9	Ex metal accounting
Pressure leach residue	25.3	Ex FEMS Metsim balance
FEMS Cu residue	18.5	Ex FEMS Metsim balance
Zn/Cu residue	5.6	Ex FEMS Metsim balance
Wastes		
Jarosite	66.2	96.4% of extra Fe to jarosite
Effluent	14321	Ex base case effluent:H_2O in
Standard flows		
Steam vented	18844	50% of steam input
Cooling water losses	11240	Ex water balance
N_2 vented	1484	As above
Other open loop flows		
Demin to PMR	910	Ex water balance
Water to sewer	7548	Ex water balance
TOTAL OUTPUTS	60964	t
INPUTS-OUTPUTS	10921	t
% ERROR	15	

AVERAGE STEAM GENERATION DATA:

INPUTS	t/mth	SOURCE
Coal	6829	Factored up for inc steam prod
Oxygen (from air)	14927	Factored up for inc steam prod
Demin water	50799	Factored up for inc steam prod
Water to ash	518	34.5% moisture
TOTAL INPUTS	73073	t
OUTPUTS		
Ash (dry)	983	Calculated
H_2O in ash	518	34.5% moisture
SO_2	48	Calculated
CO_2	17525	Calculated
H_2O	2920	Calculated
NO_2	278	Calculated
Effluent	947	Factored up for inc steam prod
Steam to PMR	1895	Ex process records
Steam to H_2	10134	Factored up for inc H_2 prod
Steam to BMR	37687	Ex FEMS pre-feasibility study
Thus steam loss at boilers	138	Calculated via bal. closure
TOTAL OUTPUTS	73073	t
INPUTS-OUTPUTS	0	

AVERAGE HYDROGEN GENERATION DATA:

	t/mth	SOURCE
INPUTS		
Natural gas (feed)	635	Calculated
Steam (incl heating)	10134	Factored up for inc H_2 prod
Inputs for heating:		
Natural gas (fuel)	614	Calculated
Oxygen (from air)	1305	Calculated
TOTAL INPUTS	12688	t
OUTPUTS		
Steam loss	9530	Calculated via bal. closure
H_2 PMR	0.8	Estimated by process staff
H_2 vented	9.00	Ex production performance report
H_2 BMR	159	Ex FEMS pre-feasibility study
CO_2 BMR	321	Calculated: 30% of total
CO_2 vented	749	Calculated :70% of total
Outputs ex heating:		
CO_2	1035	Calculated
H_2O vapour	829	Calculated
N_2	55	Calculated
TOTAL OUTPUTS	12688	t
INPUTS-OUTPUTS	0	
Electricity	6674442	Ex FEMS pre-feasibility study

Table 8.2: Estimated monthly inputs and outputs, including FEMS processing.

The new volume of effluent to Ergo was calculated from the effluent from the boilers and BMR process, as estimated in Table 8.2. The average rainfall, evaporation and change in pond level were assumed to be as for the base case, which lead to an effluent volume of 27876kℓ per month. The ratio of ammonia in the effluent to ammonia consumption for the base case was used to calculate the quantity of nitrogenous compounds in the effluent (233t/mth). The quantity of sulphur input which was unaccounted for in the FEMS Metsim balance (2.68%) was assumed to leave the process as sulphates in the effluent (total S in effluent: 126.2t/mth). The waste water output (27509t/mth) was then calculated from the total effluent less these impurities.

The reagents listed in Table 8.3, which relate to consumptions in addition to those given in the base case (Table 4.5), were excluded from the LCI according to the cut-off of ≤0.03t/t of Ni produced (whether this is taken as the base case nickel production or that for the Co scenario) (refer to section 3.3.2).

REAGENT	ADDITIONAL QUANTITY USED PER MONTH
Carbon	1102ℓ/mth
NaHS	14t
Compressed air	272000Nm^3
N9300 modifier	480kg
Ferrous sulphate	379kg
Acrysol	6.7t
Anthraquinone	64kg
Na sulphide	5kg
Na cyanide	30kg
Pre-coat powder	1700kg
Cyanex 272$^{\$}$	67kg
n-paraffin/BHT$^{\$}$	820kg
Water treatment chemicals	650kg

Table 8.3: Additional reagents required for FEMS processing by Co SX, which are excluded from the LCI.

$^{\$}$ These quantities represent the make-up quantities required to replace organic lost due to carry-over and so on.

The toxicity of Cyanex 272 has been evaluated by Cytec (Cytec Industries, 1996). The LD_{50} values (the lethal dose for 50% of the organisms) are 4.9g/kg for acute oral toxicity (rat) and >2.0g/kg acute dermal toxicity (rabbit). Cyanex 272 is non-mutagenic and the acute LC_{50} (96 hour) values (the lethal concentration for 50% of the organisms over a 96 hour period) for bluegill sunfish and rainbow trout are 46ppm and 22ppm, respectively. Toxicity of the n-paraffin diluent is very low, but it is highly flammable.

The following potential sources of additional fume generation were identified (Walker, *et al*, 1996):

- Organic fumes generated from the solvent extraction plant
- Hydrogen sulphide fumes from NaHS use in the Cu/Fe and Zn/Cd removal sections
- Sulphuric acid mist in the SX area
- Ammonia fumes from all sections post FEMS leach.

All air emissions were to be scrubbed, however, prior to being vented to atmosphere, thus preventing adverse environmental impacts. These air emissions were therefore not included in the LCI. The scrubber liquor would enter the effluent dam. With regard to aqueous effluents, a preliminary water balance completed as part of the pre-feasibility study indicated that the existing plant effluent treatment system would not need to be expanded.

8.5) EVALUATION

8.5.1) Environmental profile

A comparison of the environmental profiles of the base case and the Co scenario are presented in Table 8.4 and Figure 8.4. The detailed impact assessment for the Co SX scenario is given in Table 8.5.

Upon comparison of Table 8.5 with the base case environmental profile in Table 5.5, it is evident that the impacts due to electricity consumption per ton of nickel produced decreased significantly. This was primarily because there was no significant increase in copper production with the increase in nickel and cobalt productions, and it is the copper electrowinning process which consumes a significant portion of the electricity. The Co SX itself and the other additional

processes in the Co SX scenario consume comparatively little electricity. Milling of the FEMS material is also less energy intensive than for the milling of matte, as this material is of a fine particle size.

The impacts associated with steam generation per ton of nickel produced decreased for the Co scenario. The environmental impacts associated with hydrogen generation per ton of nickel produced increased for the Co scenario, however. This was due to the increased Co to Ni production ratio, and the increased demand for hydrogen for reduction of these metals.

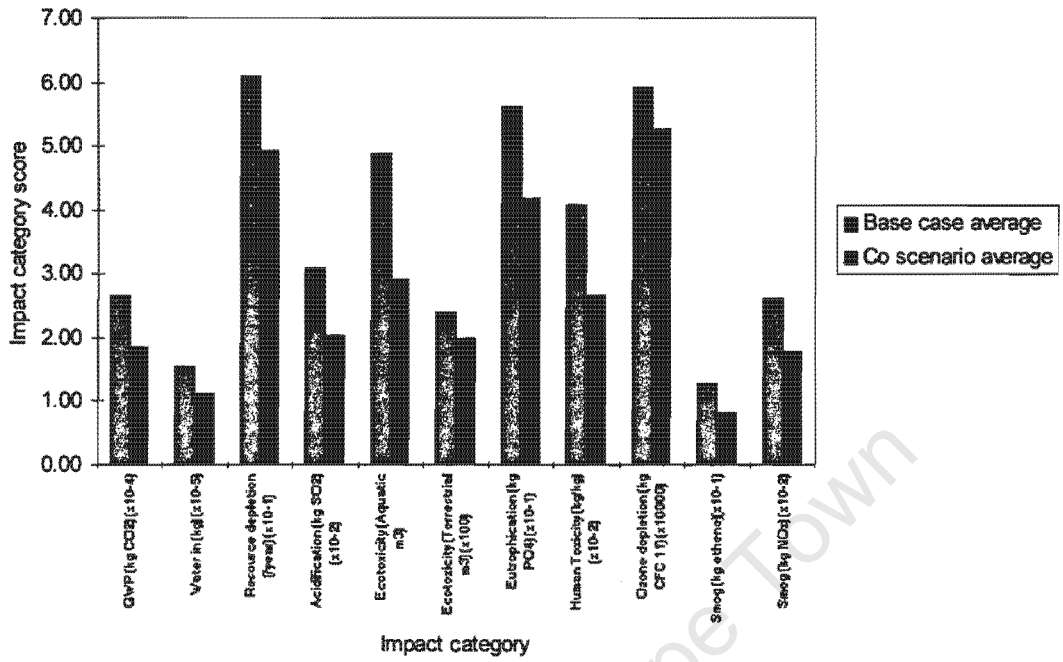
IMPACT CATEGORY	BASE CASE AVERAGE	Co SCENARIO AVERAGE	% DIFFERENCE
GWP (kg CO_2) ($x10^{-4}$)	2.66	1.84	-30.8
Water in (kg) ($x10^{-5}$)	1.53	1.11	-27.5
Resource depletion (/year) ($x10^{-1}$)	6.09	4.92	-19.2
Acidification (kg SO_2) ($x10^{-2}$)	3.08	2.03	-34.1
Ecotoxicity (Aquatic m^3)	4.88	2.90	-40.6
Ecotoxicity (Terrestrial m^3) ($x10^2$)	2.38	1.98	-16.8
Eutrophication (kg PO_4) ($x10^{-1}$)	5.62	4.17	-25.8
Human Toxicity (kg/kg) ($x10^{-2}$)	4.06	2.64	-35.0
Ozone depletion (kg CFC 11) ($x10^4$)	5.91	5.26	-11.0
Smog (kg ethene) ($x10^{-1}$)	1.27	0.81	-36.2
Smog (kg NO_x) ($x10^{-2}$)	2.59	1.76	-32.0

Table 8.4: Environmental profiles for the base case and the Co scenario.

Impact category	TOTAL	BMR total	BMR process	O_2 from air decomposition	N_2 from air decomposition	H_2SO_4	HNO_3	Ammonia	H_2 total	H_2 produced	Natural gas delivered UK	Steam total	Steam generated	Coal, hard UK	SA elec	Effluent
GWP (kg CO_2)	**18351**	**2336**	0.00	365	241	132	38.7	1560	**1185**	995	190	**11190**	9777	1414	**3640**	**0.00**
Water in (kg)	**110565**	**47862**	12886	16136	10647	3035	148	5010	**1029**	0.00	1029	**47494**	28629	18865	**6822**	**7358**
Resource depletion (/year)	**49.2**	**13.5**	0.00	1.28	0.84	0.62	0.25	10.5	**13.3**	0.00	13.3	**18.9**	0.00	18.9	**3.51**	**0.00**
Acidification (kg SO_2)	**203**	**17.8**	0.00	2.29	1.51	3.35	0.28	10.4	**1.07**	0.00	1.07	**138**	135	2.61	**45.7**	**0.00**
Ecotoxicity (Aquatic m^3)	**2.90**	**0.03**	0.00	0.01	0.01	0.00	0.00	0.01	**0.02**	0.00	0.02	**0.49**	0.00	0.49	**0.44**	**1.92**
Ecotoxicity (Terrestrial m^3)	**1.98E-02**	**1.21E-02**	0.00E+00	3.99E-03	2.63E-03	1.48E-03	1.42E-04	3.86E-03	**1.35E-03**	0.00E+00	1.35E-03	**6.33E-03**	0.00E+00	6.33E-03	**5.01E-07**	**0.00E+00**
Eutrophication (kg PO_4)	**41.7**	**1.64**	0.00	0.10	0.07	0.03	0.04	1.40	**0.10**	0.00	0.10	**25.4**	20.2	5.28	**1.51**	**13.0**
Human Toxicity (kg/kg)	**264**	**26.8**	0.00	3.39	2.24	4.18	0.40	16.5	**1.80**	0.00	1.80	**157**	153	4.38	**77.4**	**0.76**
Ozone depletion (kg CFC 11)	**5.26E-04**	**3.14E-04**	0.00E+00	8.50E-05	5.61E-05	2.42E-05	3.59E-06	1.45E-04	**1.02E-04**	0.00E+00	1.02E-04	**1.10E-04**	0.00E+00	1.10E-04	**0.00E+00**	**0.00E+00**
Smog (kg ethene)	**8.08**	**2.23**	0.00	0.08	0.05	0.03	0.04	2.02	**0.14**	0.00	0.14	**0.53**	0.00	0.53	**5.18**	**0.00**
Smog (kg NO_x)	**176**	**7.35**	0.00	0.73	0.48	0.24	0.19	5.71	**0.66**	0.00	0.66	**156**	155	1.38	**11.5**	**0.00**

Table 8.5: Overall impact assessment for the cobalt SX scenario.

Figure 8.4: Comparison of the impact assessments for the cobalt scenario and the base case



It is evident that the trend of lower specific environmental impacts (per ton of nickel produced) with increasing nickel production has occurred, even with the change in process technology. It was not possible to directly compare the impacts associated with this new Co SX process technology with that of the base case, as there were no data points available in this range of nickel production. The base case is also only valid for that specific ratio of products, however. Thus a Ni production of 1792.5t/mth would relate to a Cu production of 764t/mth, and a Co production of 13.4t/mth for the base case. For this scenario, however, the ratio of products was considerably different, with actual Cu and Co productions of 413 and 42.9t/mth respectively, due to the processing of a different type of material. This mix of products could not be produced using the base case technology and related reagents and utilities (as previously discussed), thus the corresponding environmental profile will differ. Caution should therefore be exercised when comparing the results of the Co SX scenario to that of the base case.

8.5.2) Sensitivity analysis

The quantity of cobalt in the effluent to Ergo was increased from that of the base case in line with the increased Co production, in order to assess the sensitivity of

the impact scores to changes in this value. The concentration of Co in the effluent from the BMR was increased by a factor of six (to 0.21g/ℓ, which related to 2.98t/mth Co in the effluent), as this was the relative increase in Co production from the base case. The only impact score which changed was human toxicity, which increased by 1% from 264 to 267kg/kg. This change was not deemed significant, although the inherent limitations of the impact scores derived for this category must be remembered (refer to section 5.3.3H).

The effect on the environmental profile of including some of the excluded reagents was then determined. NaHS was included as it was the excluded reagent which would be used in the largest quantities. The general inorganic chemical database was utilised, as a specific LCI data for NaHS was unavailable in the PEMS software. The phosphoric acid database was used to obtain a very rough approximation of the environmental impacts associated with Cyanex 272 manufacture. The reference for both of these databases is given as the Eidgenössische Technische Hochschule (document reference: ETH-ENET 30179) (Pira, 1998).

The LCI for n-paraffin was taken from the Tenside Surfactants/detergents database in PEMS version 4. It represents an industry average, and was compiled from a variety of sources by the European LCI Surfactant Study Group and Franklin Associates Limited (Pira, 1998). The system boundaries for this database included all production steps from extraction of raw materials to refining and final processing. Manufacture and maintenance of capital equipment, including heating and lighting, were excluded. The environmental profile obtained upon inclusion of these reagents is presented in Table 8.6.

It is evident upon comparison of the environmental profiles in Table 8.6, that the inclusion of the additional reagents did not increase the environmental profile scores significantly, thus their exclusion appears to be justified. The relevance of the LCI data used for NaHS and Cyanex 272 is debatable, however. Should the introduction of Co SX be considered again in the future, relevant information regarding the manufacture of these compounds should be obtained from the suppliers for LCA purposes.

IMPACT CATEGORY	Co SCENARIO	Co SCENARIO INCLUDING SOME EXCLUDED REAGENTS	% DIFFERENCE
GWP (kg CO_2)	18351	18359	0.04
Water in (kg)	110565	110628	0.06
Resource depletion (/year)	49.2	49.2	0
Acidification (kg SO_2)	203	203	0
Ecotoxicity (Aquatic m^3)	2.90	2.90	0
Ecotoxicity (Terrestrial m^3)	1.98×10^{-2}	1.99×10^{-2}	0.51
Eutrophication (kg PO_4)	41.7	41.7	0
Human Toxicity (kg/kg)	264	264	0
Ozone depletion (kg CFC 11)	5.26×10^{-4}	5.32×10^{-4}	1.14
Smog (kg ethene)	8.08	8.08	0
Smog (kg NO_x)	176	176	0

Table 8.6: The effect on the environmental profile of including some of the excluded reagents in the LCI.

(Additional reagent inclusions: NaHS (base case + additional), ferrous sulphate (base case + additional), n-paraffin, and Cyanex 272).

The potential contribution of transportation of the FEMS material to the environmental profile was then investigated. The material would be transported approximately 12000km by sea freighter from the Far East to Durban harbour (distance obtained from major shipping routes, as published by Eagle Freight and 90% utilisation of the transoceanic freighter was assumed as a first approximation). The material would then be transported a further 600km by rail from Durban to Springs, Gauteng (again a utilisation of 90% was assumed). The resultant environmental profile is shown in Table 8.7. It is evident that although the impact scores increased upon the inclusion of FEMS transportation, the scores remained smaller than those relating to the base case (with the exception of the ozone depletion score, which was slightly higher than that for the base case, refer to Figure 8.4), thus the exclusion of the transport step did not significantly alter the

conclusions and its exclusion is deemed valid. (Note that the percentage differences in Table 8.7 were highest for the two scores which were low values).

IMPACT CATEGORY	Co SCENARIO	Co SCENARIO INCLUDING FEMS TRANSPORTATION	% DIFFERENCE
GWP (kg CO_2)	18351	18438	0.47
Water in (kg)	110565	111348	0.71
Resource depletion (/year)	49.2	49.8	1.2
Acidification (kg SO_2)	203	205	0.99
Ecotoxicity (Aquatic m^3)	2.90	2.92	0.69
Ecotoxicity (Terrestrial m^3)	1.98×10^{-2}	2.33×10^{-2}	18
Eutrophication (kg PO_4)	41.7	41.8	0.24
Human Toxicity (kg/kg)	264	268	1.5
Ozone depletion (kg CFC 11)	5.26×10^{-4}	6.13×10^{-4}	17
Smog (kg ethene)	8.08	8.16	0.99
Smog (kg NO_x)	176	177	0.57

Table 8.7: The effect of the inclusion of transportation of FEMS material on the environmental profile.

8.5.3) Functional unit evaluation

Due to the fact that the production of cobalt increased significantly from the base case, the relevance of using the functional unit based on nickel production volumes was considered. The Ni to Co ratio decreased from 134:1 in the base case, to 42:1 in the Co scenario and the Ni:Co price differential is approximately 1:10. The use of a financially-based functional unit was thus considered, based on the quantity of material brought into the BMR to derive a unit of revenue from nickel, cobalt, and copper production (revenue generated from by-products was excluded, including the PGM concentrate, for which the revenue generated is ascribed to the PMR).

An overall functional unit (in $/month) was obtained by adding up individual units derived from the mass of each material processed per month multiplied by the revenue generated for each ton treated (derived from the base metals content of the material, as shown in Table 8.8). The calculation below is based on the overall

monthly average metal prices for the period considered in the base case (01/95 to 07/97), as shown in Table 8.9.

ELEMENT (IN %)	IMPALA MATTE	Ni SULPHATE	Co NITRATE	FEMS	WMC MATTE
Ni	52	21	0	51	72.2
Cu	31	0	0	0.01	0.3
Co	0.3	0.15	1.4	2.86	1.14
t/mth	1343	1124	118	1176	318

Table 8.8: Percentage base metal compositions of raw materials and quantities processed.

METAL	AVERAGE PRICE IN $/t
Nickel	7746.6
Copper	2573.4
Cobalt	57556

Table 8.9: Overall average monthly base metal prices for the period 01/95 to 07/97 inclusive (taken from the *Metal Bulletin*).

The functional unit for Impala matte was thus calculated as follows:

Impala matte = ((0.52*7746.6) + (0.31*2573.4) + (0.003*57556))$/t * 1343t/mth

= 6.7 X 10^6 $/month

Similarly, the financial units were calculated for the other raw materials processed in the base case, from the data given in Table 8.8. (The other toll refining matte inputs were excluded, as each of these materials processed was of a relatively small quantity).

The overall functional unit for the base case monthly average was thus:

6.7 x 10^6 $/month (Impala matte) + 1.9 x 10^6 $/month (Ni sulphate)

+ 9.5 x 10^4 $/month (Co nitrate)

= 8.7 x 10^6 $/month.

In addition to this, the Co scenario would include the following:

6.6×10^6 \$/month (FEMS material) + 2.0×10^6 \$/month (WMC matte),

thus the overall functional unit for the Co SX case would be:

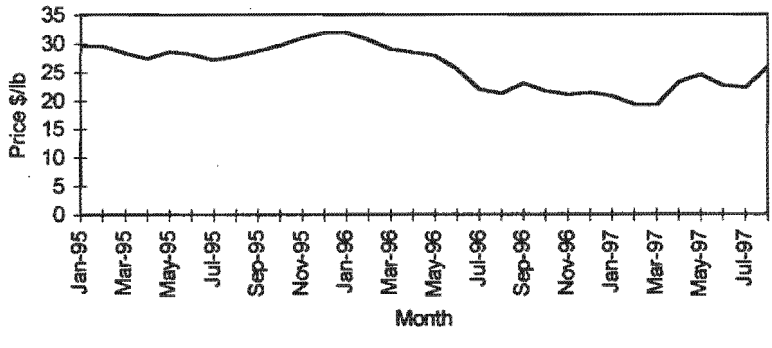
1.7×10^7 \$/month.

Thus the FEMS material would dominate this functional unit calculation.

It is evident from the difference between the functional units for the base case and for the Co SX scenario, that the environmental profile of the Co SX scenario case would be even more favourable than the base case if this financial functional unit was used, due to the division of the Co SX impact scores by a larger factor (the ratio of nickel productions for the FEMS case to the average base case was 1.85, while that for the functional units is 1.95). The same trend as obtained with the nickel production based functional unit, of decreased environmental profile scores for the FEMS/Co SX case compared to the base case, would thus be obtained.

The nickel production-based functional unit is preferred, however, because the metal prices (particularly that of cobalt (Searle, 1997)) fluctuate significantly on a daily and monthly basis. The monthly average cobalt metal prices are presented in Figure 8.5 as an example (the %RSD was 15%). The fluctuations in material composition from batch to batch within a month would also cause inaccuracies in the functional unit calculation, due to the current usage of monthly average compositions. These two factors could therefore introduce a significant source of error into the LCA, thus the nickel functional unit is deemed to be more suitable. It also enables bench-marking and comparison of results with those from other similar studies.

Figure 8.5: Cobalt metal price
(ex the *Metal Bulletin*)



It is also acknowledged that an economically-based functional unit derived in the manner described is a means of allocation. According to the ISO 14041 standard, allocation by economic value is only to be used when allocation based on physical relationships within the system cannot be established (ISO, 1998). In the case of the BMR process, there are relationships between the inputs and outputs and the functional outputs delivered by the system.

8.6) CONCLUSION

Although this first-order LCA indicated that the environmental profile scores per ton of nickel produced would improve should FEMS material be processed and Co SX be introduced, it must be emphasised that this is a preliminary assessment. Should serious consideration be given by Impala Platinum to the introduction of such a process option in future, it would be necessary to confirm these findings by a more in-depth study, which would include, for example, more detail on the potential environmental impacts associated with the organic solvent and the fate of cadmium. A more detailed effluent balance (including the quantity of organic which would report to the effluent) should also be done. The study would need to be adapted slightly for the specific Co-bearing material of interest, and ideally the effect of the residues on the smelter operations should also be considered.

Sensitivity studies revealed that the inclusion of additional reagents, transportation, and increased Co in the effluent to Ergo respectively did not significantly change the overall impact scores.

These factors fell outside the system boundary for this study, however, and were thus excluded. The results of this first-order environmental assessment indicated that the process option discussed would not lead to an increase in environmental impact scores per ton of nickel produced, as compared to the base case (the environmental impacts would be approximately 30% lower than for the base case (or approximately 20% lower when transportation of the FEMS material is included, in which case the ozone depletion score would also be 4% higher than the base case)). The total monthly environmental impacts would be approximately 36% higher, however, due to the increased mass of nickel produced.

In processing FEMS material, the nickel production would increase by 85%, the Co production by 494%, and the copper production by 0.2%. This would relate to an increase in revenue generated from these base metals of approximately 94% (based on the metal prices given in Table 8.9).

Chapter 9: SCENARIO C: EVALUATION OF THE ESTABLISHMENT OF AN ION EXCHANGE EFFLUENT TREATMENT FACILITY

9.1) INTRODUCTION

Impala Platinum Ltd Refineries has made a concerted effort over the years to reduce water consumption (refer to section 4.6.2), as well as to treat effluent streams for recycling (by reverse osmosis). Effluent derived from a number of processes at Impala's BMR site is, however, routed to the effluent pond on the premises, as was shown in Figure 4.5 and in more detail in Figure 9.1.

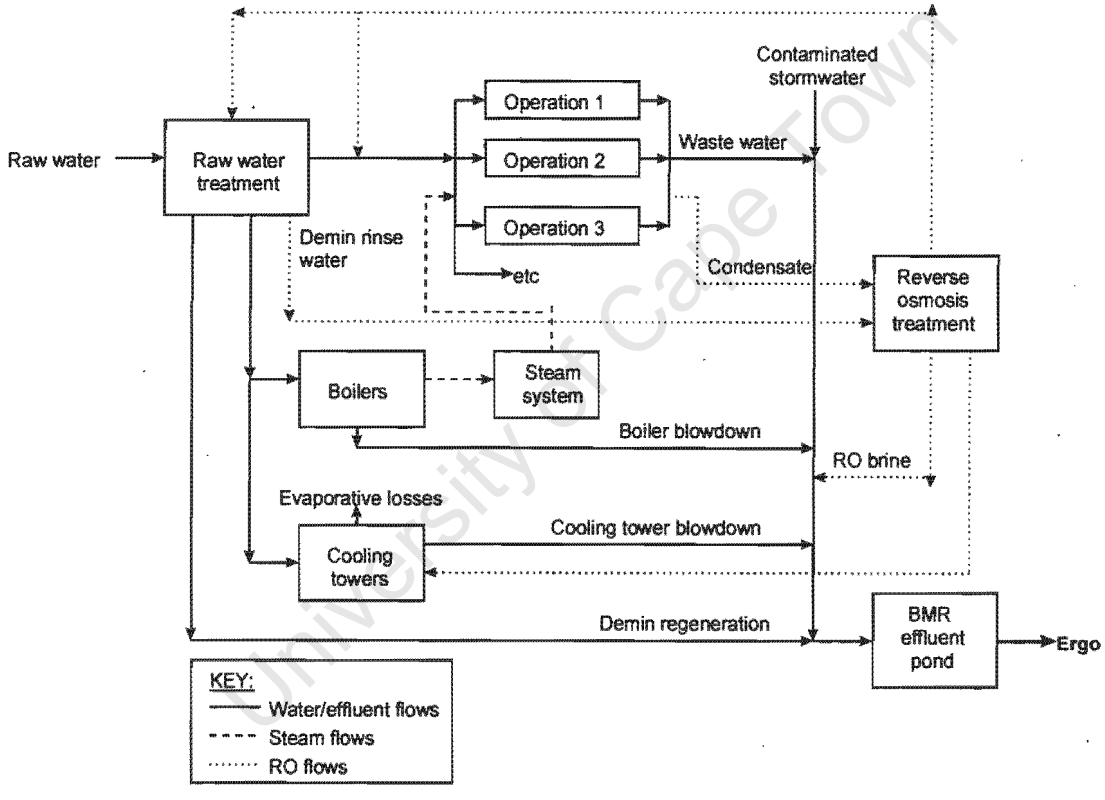


Figure 9.1: Schematic diagram showing water use and treatment at Impala's BMR.

Effluent from the BMR effluent pond is currently pumped to Ergo, for use in slimes dam recovery processes. It has been acknowledged that this is not a permanent outlet for the BMR's liquid effluent, thus alternatives are being investigated. It would be advantageous to treat the effluent in-house so that the treated water could be recycled, thereby reducing the consumption and thus cost of Rand Water Board water. Costs would also be reduced by recovery of the base metal ions present in the effluent (it has been estimated that 24t of Ni, 0.8t of Co, and 2.9t of Cu were lost

in the effluent between July 1997 and June 1998 (Ralph, 1998b)). In-house treatment would also lend itself to improved control of the fate of the effluent, and thus the environmental impacts associated with it.

Various methods of recovering metals from effluent streams have been or are being developed (Vinnecombe, 1991), including capsulated membrane extraction (Smit, 1997), ultrafiltration (Kotzian and Wakeman, 1997), and ion exchange. Upon consideration of the quality of the pond effluent, and the cost of the different technologies, it was decided that ion exchange (IX) technology should be tested for this application.

Small scale IX testwork was thus done in conjunction with Chematron Products (Pty) Ltd, during the first half of 1998. (Effluent was processed through a unit containing 10ℓ of resin at 150ℓ/hr). Following this, a brief preliminary full scale plant proposal has been compiled, upon which this case study is based. The process design, as proposed by Chematron, will now be outlined.

9.2) PROCESS DESIGN

The ion exchange resin which was tested was Lewatit TP 207, produced by Bayer. It is classified as a macroporous chelating resin, and has imino-diacetic acid functional groups (Bayer, 1997). Sodium ions, supplied by caustic buffering after sulphuric acid stripping, are selectively displaced by divalent cations. Thus Ni^{2+}, Cu^{2+}, Co^{2+}, and Ca^{2+} ions would be removed from the BMR effluent by the resin. The resin has a theoretical capacity of 40g (Ni + Co)/ℓ resin, but an actual capacity of 22-24g/ℓ was used for the process design. This large safety factor was incorporated in order to prevent break-through occurring due to fluctuations in effluent quality. The resin is expected to last at least four years. It has a selectivity of $Cu^{2+} > Ni^{2+} > Co^{2+}$. Sodium ions displaced from the resin or present in the effluent stream would pass through the resin, as would anions, and will therefore be present in the raffinate. The basic flowsheet is shown in Figure 9.2.

The product water (raffinate) would report to the RO plants, which are currently under-utilised, for further purification before being polished by the demin units. It would then be used as process water, boiler feed water, and so on.

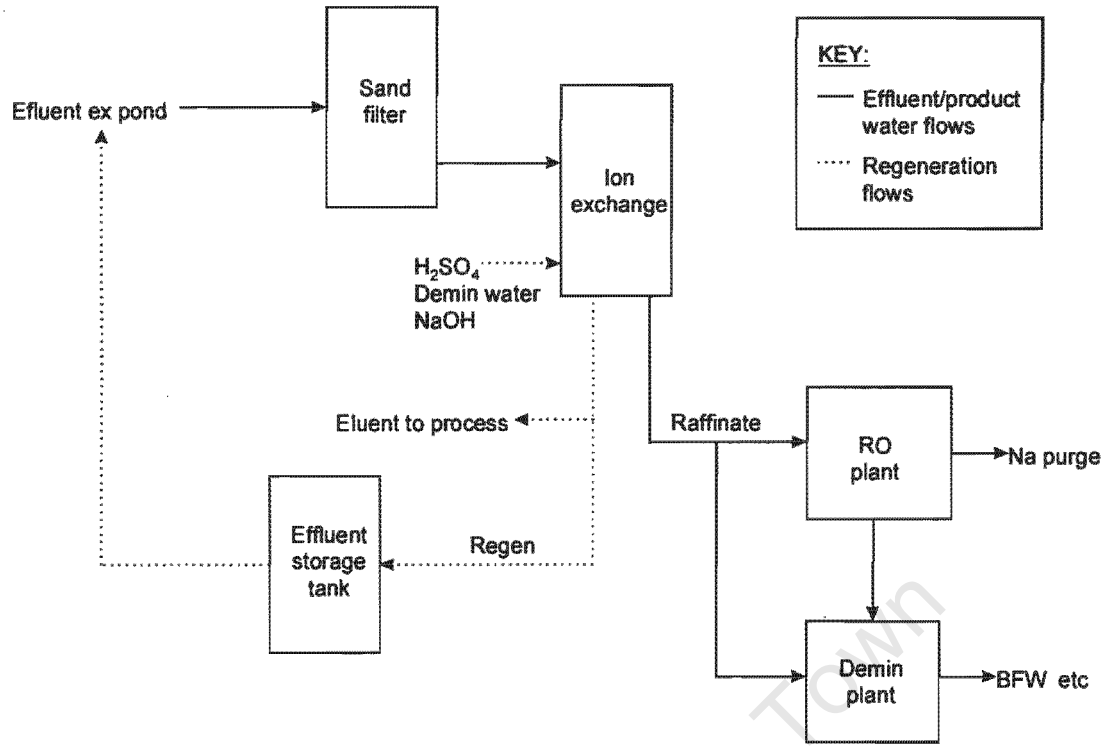


Figure 9.2: Proposed ion exchange effluent treatment plant.

It has been established that the RO plants are capable of processing water containing the sodium concentration found in the IX product water (as determined by the preliminary testwork). The accumulation of sodium ions in the system could be a potential problem, however, as these ions would return to the effluent pond via the RO brine or the demin regeneration liquor. A bleed stream or purge for the sodium ions would therefore be necessary by the crystallisation of the RO brine effluent stream, for example. The sodium chloride/sodium sulphate could then be disposed of by landfill or by addition to the ammonium sulphate by-product (within the constraints of the specifications for this by-product which stipulates that the nitrogen content must be greater than 20.55%). The condensate from the crystallisation process could be treated by the demin plants or be returned to the effluent pond, and subsequently be reprocessed.

The IX regeneration liquors would be routed back to the effluent pond, with the exception of the eluate stream containing the metal ions, which could either be recycled directly to the BMR process, or be precipitated by means of caustic addition. The solids could then be returned to Minpro for reprocessing or added to the ammonium sulphate product (within the impurity content specifications of less

than 0.054% Ni and Co respectively). In the case of the former option, the base metal ions would ultimately report to the respective metal products. As the ammonium sulphate is used as a fertiliser, the metal ions present would serve as trace elements for agriculture, although, as a worst case scenario, their ultimate fate could be to ground or surface waters. The filtrate from the caustic addition step would be routed to the effluent pond.

9.3) GOAL DEFINITION AND SCOPING

9.3.1) Purpose of the scenario and LCA boundaries

The purpose of this case study was to provide a preliminary environmental assessment of the proposed effluent treatment by ion exchange, in order to determine the applicability of using the base environmental model as a tool for the evaluation of different waste treatment options. Two possible process options, within the IX framework, and the base case were thus compared on an environmental impact basis. Other process options could similarly be assessed. The same process boundary was used as for the base case. This allows for flexibility of the study, in terms of possible future assessments of additional process options or parameter changes. The sub-system boundaries for each of the effluent treatment cases considered are shown in Figures 9.3 and 9.4.

The first process option (a) involved the recycling of the metal eluate directly to the BMR process, thus the metal ions present would ultimately report to the respective metal products. In the second process option (b), the metal eluate is precipitated by caustic addition. The solids then leave the BMR as an open loop output (via the ammonium sulphate by-product or by returns to Mineral Processes). This option is included due to the concern that the direct addition of the eluate to the process may have adverse effects on efficiencies and purity of products, as given in case (a). In addition, the cost of recycling this stream may not warrant the savings in terms of recovered metals (inclusion in the ammonium sulphate would thus be employed). The filtrate from caustic precipitation is routed back to the effluent pond.

In both case studies, the RO brine is crystallised in order to purge sodium from the process, and is then added to the ammonium sulphate by-product (an open loop output) and the condensate is recycled to the demin plants.

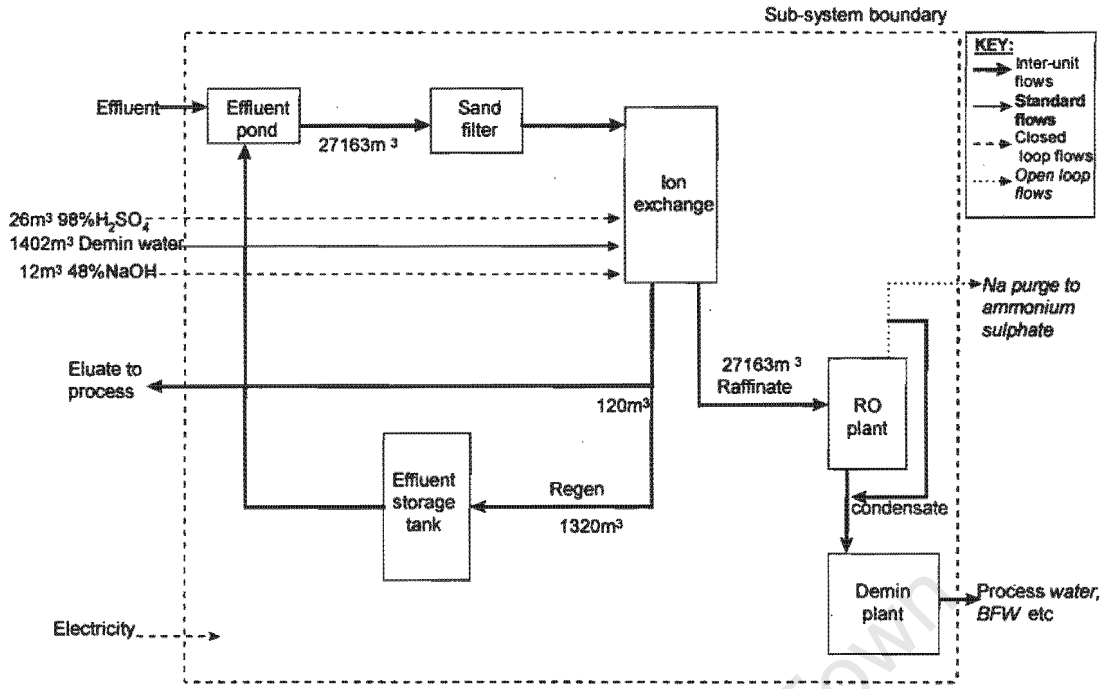


Figure 9.3: Effluent treatment case (a) sub-system boundary diagram, indicating monthly flowrates.

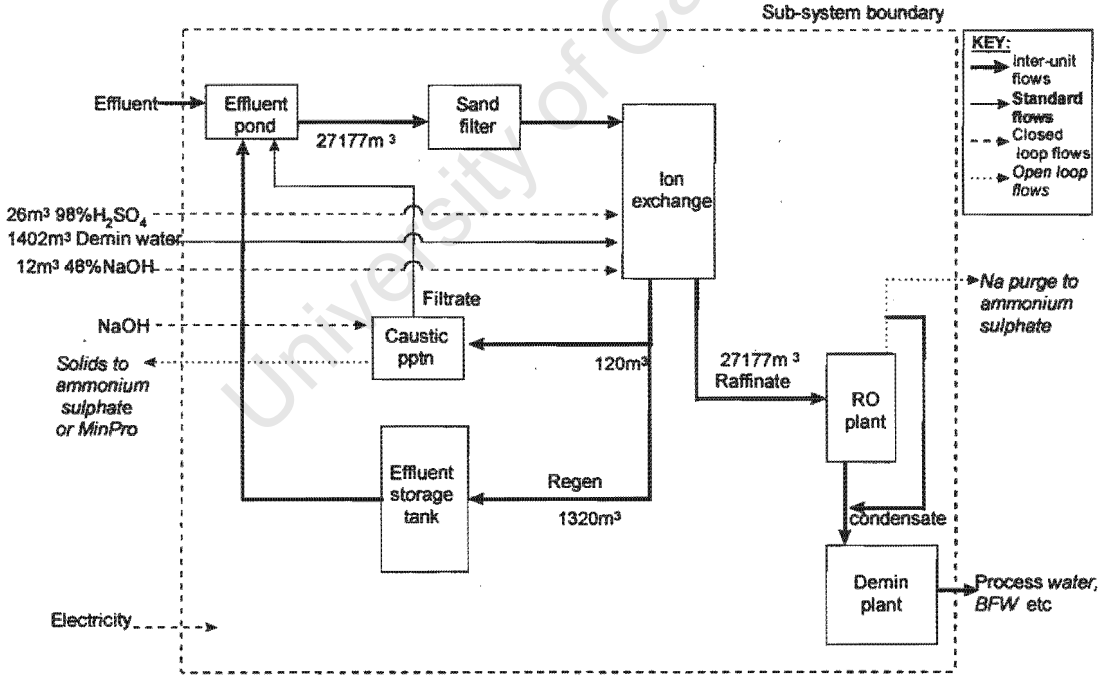


Figure 9.4: Effluent treatment case (b) sub-system boundary diagram, indicating monthly flowrates.

9.3.2) Functional unit and data sources

One ton of nickel produced was used as the functional unit for this scenario, as the product ratio did not vary significantly from that of the base case for case (a), and was the same as the base case for case (b).

The project proposal, as submitted by Chematron, was the primary source of information relating to the ion exchange process. Information regarding current demin and RO plant capacities and proposed process options was obtained from process personnel and the BMR Project Department staff. Information relating to the current fate of the effluent was obtained from the Environmental Department of Ergo. It should be noted that the information and data used in this scenario was of a more approximate nature than that used for the base case, as this project is still in the very early stages of process design. An error of 15-20% is thus estimated, based on the accuracy required for the initial Chematron report, and that of the other data used.

9.3.3) Assumptions and limitations

For both cases, it is assumed that all of the treated effluent is utilised in the BMR, and thus the IX facility effectively reduces the quantity of RWB water consumed and no BMR effluent is routed to Ergo or any other operation. The average analytical effluent composition was used, although high fluctuations in the effluent quality do occur. A number of assumptions were made with respect to the LCI calculations. These will be explained in section 9.4.3.

The environmental impacts associated with the production and disposal of the IX resin are excluded, as is consistent with the similar exclusions made for the demin water resins in the base case. It was assumed that all of the IX product water will be further polished by both the RO and demin plants. The current RO plants have sufficient capacity to process this water.

The electricity consumption related to the pumping of effluent to Ergo is excluded from the base case, as it is presently for the account (in the economic not environmental sense) of Ergo, thus it is not metered by Impala. For the two IX treatment case studies, the two pumps presently in use by Ergo would be used to pump the effluent to the new IX plant site. In both case studies only the pumping

requirements in addition to the use of these two pumps are included in the additional electricity requirement calculations, in order to achieve consistency with the base case.

Impacts associated with the production and maintenance of capital equipment are excluded, as in the base case. Transport of the additional reagents to the BMR site were considered to be of relatively minor impact, and thus were also excluded from this preliminary assessment.

9.4) DATA COLLECTION AND LCI

9.4.1) Average effluent analysis

Table 9.1 gives the average monthly effluent analysis, for the time period covered in the base case, as well as the percentage relative standard deviations between the monthly results. It is evident that the composition of the effluent leaving Impala's BMR effluent pond is very variable, due to significant daily fluctuations in the composition of the input streams. The analysis of the effluent as of 04/98, which was used in the IX testwork is also included in Table 9.1. Upon comparison of the two sets of analyses, it is appears that effluent control has improved considerably with respect to base metal ions. (This was confirmed by comparison with additional recent monthly averages).

9.4.2) The base case: Disposal of effluent to Ergo

The effluent from the pond passes through bag filters (after lime dosing if necessary) prior to being pumped to Ergo's Geduld Booster Station, from which it is presently used to recover two slimes dams in the vicinity. Approximately 18000t/day of slimes dam sludge is processed by Ergo, which requires the use of 100Mℓ of water a day. Of this, approximately 25-30Mℓ is water which is added to the process to replace evaporative losses and the remainder is recycled water from Ergo's tailings pond. It is from the large surface area of this pond that the majority of the evaporation occurs. There are also losses due to seepage, although these are small in comparison to the evaporative losses.

The average monthly effluent flow to Ergo from Impala for the period 01/95 to 07/97 was 26073kℓ/month (roughly 1Mℓ/day), which is approximately 3% of Ergo's total

water input. Other sources of water to Ergo are local municipalities and the Rand Water Board, which together provide approximately 10Mℓ of potable water per day for high purity water uses. The balance of water addition is from underground water from East Rand Proprietary Mines (ERPM) in Boksburg (Geldenhuys, 1998, and Dennis, 1998). Metal ions which originated from Impala effluent will, as the worst case scenario (used in the base case), enter the groundwater due to seepage during slimes dam recovery or during storage in Ergo's tailings pond, although the extent of water seepage is presently unquantified.

The relevant inputs and outputs relating to this base case are given in Table 9.2. The kg/month of constituents were calculated from the average effluent analysis and from the average monthly effluent flow to Ergo. The metals and ions contained in the base case were those included in the mass balance (Ni, Cu and Co), and those present in relatively large concentrations (NH_3 and sulphates). Additional elements and ions (Ca, Mg, Na, NO_3^-) which were present in the effluent at concentrations of >15ppm, were included for the base case in this scenario to aid in the comparison of the different effluent treatment options. (These inclusions resulted in a slightly higher eutrophication score than that shown in Table 5.5, due to the nitrates). The mass of waste water output was calculated by difference (total effluent to Ergo less impurities).

The rain component of the effluent was also excluded from the water usage impact category of the environmental profile, so that a change in RWB water usage would be more evident.

The environmental profile thus produced is presented in Table 9.3.

ANALYTE	AVERAGE ANALYSIS AS PER BASE CASE (01/95-07/97)	% RSD OF THIS AVERAGE	ANALYSIS OF IX TESTWORK FEED SOLUTION
Ni	212	51	88
Cu	27	188	3.9
Co	17	46	7.6
Fe	1	53	<0.05
Se	2	32	N/A*
Te	2	0	N/A
Zn	0.8	33	N/A
NH_3 (g/ℓ)	5.26	48	2.35
SO_4 (g/ℓ)	3.47	99	5.70
pH	7.0	11	7.6
Al	N/A	N/AP[$]	<0.15
Ba	N/A	N/AP	0.07
Ca	86[#]	N/AP	79
Mg	20[#]	N/AP	18
Mn	2[#]	N/AP	1.0
Na	583[#]	N/AP	654
Si	7[#]	N/AP	12
K	13.5[#]	N/AP	N/A
NO_3^-	55[#]	N/AP	N/A
Conductivity (mSm^{-1})	N/A	N/AP	1141
Turbidity (NTU)	N/A	N/AP	5.05
Suspended solids	N/A	N/AP	21
COD (mgO_2/ℓ)	N/A	N/AP	76

Table 9.1: Average base case and IX testwork effluent analyses.

All concentrations in ppm, unless otherwise stated.

* N/A: not analysed. # Spot sample analysed for this analyte. $ N/AP: not applicable.

LCI INPUTS	**t /MONTH**
Effluent (ex BMR and steam gen.)	13466
Rainwater	13189
TOTAL INPUTS	26655
LCI OUTPUTS	
Ni (waterborne)	5.5
Co (waterborne)	0.44
Cu (waterborne)	0.70
Ammonia as Nitrogenous compounds (waterborne)	137
Sulphates (waterborne)	91
Ca (waterborne)	2.2
Mg (waterborne)	0.5
Na (waterborne)	15.2
NO_3^- (waterborne)	1.4
Water vapour (evaporation)	912
Waste water	25489
TOTAL OUTPUTS	26655

Table 9.2: Effluent inputs and outputs relating to the base case.

Impact category	TOTAL	BMR total	BMR process	O_2 from air decomposition	N_2 from air decomposition	H_2SO_4	HNO_3	Ammonia	H_2 total	H_2 produced	Natural gas delivered UK	Steam total	Steam generated	Coal, hard UK	SA elec	Effluent
GWP (kg CO_2)	**26611**	**2566**	0.00	354	168	288	39	1717	**1063**	893	170	**16442**	14365	2077	**6541**	**0.00**
Water in (kg)	**139401**	**56442**	21098	15654	7412	6615	147	5516	**923**	0.00	923	**69778**	42060	27718	**12259**	**0.00**
Resource depletion (/year)	**60.9**	**14.9**	0.00	1.24	0.59	1.36	0.25	11.5	**11.95**	0.00	12.0	**27.7**	0.00	27.7	**6.31**	**0.00**
Acidification (kg SO_2)	**308**	**22.3**	0.00	2.22	1.05	7.30	0.28	11.4	**0.96**	0.00	0.96	**203**	198.8	3.84	**82.2**	**0.00**
Ecotoxicity (Aquatic m^3)	**4.88**	**0.03**	0.00	0.01	0.005	0.01	0.00	0.01	**0.02**	0.00	0.02	**0.72**	0.00	0.72	**0.79**	**3.33**
Ecotoxicity (Terrestrial m^3)	**2.38E-02**	**1.33E-02**	0.00E+00	3.87E-03	1.83E-03	3.22E-03	1.42E-04	4.25E-03	**1.21E-03**	0.00E+00	1.21E-03	**9.30E-03**	0.00E+00	9.30E-03	**9.01E-07**	**0.00E+00**
Eutrophication (kg PO_4)	**56.3**	**1.80**	0.00	0.10	0.05	0.07	0.04	1.54	**0.09**	0.00	0.09	**37.4**	29.6	7.76	**2.71**	**14.3**
Human Toxicity (kg/kg)	**406**	**32.6**	0.00	3.29	1.56	9.12	0.40	18.2	**1.62**	0.00	1.62	**231**	225	6.44	**139**	**1.23**
Ozone depletion (kg CFC 11)	**5.91E-04**	**3.38E-04**	0.00E+00	8.25E-05	3.91E-05	5.28E-05	3.59E-06	1.60E-04	**9.17E-05**	0.00E+00	9.17E-05	**1.61E-04**	0.00E+00	1.61E-04	**0.00E+00**	**0.00E+00**
Smog (kg ethene)	**12.7**	**2.45**	0.00	0.08	0.04	0.06	0.041	2.23	**0.13**	0.00	0.13	**0.78**	0.00	0.78	**9.30**	**0.00**
Smog (kg NO_x)	**259**	**8.04**	0.00	0.71	0.34	0.52	0.19	6.29	**0.59**	0.00	0.59	**230**	228	2.02	**20.6**	**0.00**

Table 9.3: Overall impact assessment for the production of one ton of nickel as per the BMR base case, including additional effluent constituents and excluding rainwater.

9.4.3) Case (a) and case (b): Data relating to the IX treatment of effluent

An expected average effluent feed composition, which was calculated by Chematron and used in the proposal, is shown in Table 9.4. The metal deportments estimated from the testwork are also included (Chematron, 1998) (Note that sodium would report to the product water, as monovalent ions are not retained on the resin).

ELEMENT	FEED (kg/mth)	PRODUCT WATER (kg/mth)	METALS IN PRODUCT WATER AS A % OF FEED	ELUATE (kg/mth)	METALS IN ELUATE AS A % OF FEED
Ni	1500	27	1.8	1473	98.2
Co	210	27	12.9	183	87.1
Cu	150	30	20.0	120	80.0
Ca	1200	672	56	528	44
Mg	900	474	53	426	47

Table 9.4: Expected metal deportment.

The total quantity of divalent ions in the input stream was thus 3960kg/mth. However, the loading (in terms of the mass of metal ions retained by the resin) corresponding to the average effluent analysis for the period considered in the base case and given in Table 9.1 was 9436kg/mth (2.4 times larger). For the same volume of effluent processed by the same quantity of resin, twice as many regenerations would then be required (the ion input in excess of this would be contained by the unused resin capacity). (Note: the additional reagent requirements due to the increase in regenerations was taken into account). The metal deportments, as given in Table 9.4, were applied to this average effluent composition, to give the expected product water and eluate compositions, as given in Table 9.5.

ELEMENT	FEED (kg/mth)	PRODUCT WATER (kg/mth)	ELUATE (kg/mth)
Ni	5527	99.5	5427.5
Co	443	57	386
Cu	703	141	562
Ca	2242	1256	986
Mg	521	276	245

Table 9.5: Metal deportments used for case studies.

The changes to the LCI for the two case studies are presented in Tables 9.6 and 9.7, while the additional excluded reagents are given in Table 9.8. All calculations were based upon the average effluent composition as used in the base case. The quantity of effluent treated was calculated by mass balance closure, as indicated in Tables 9.6 and 9.7 (it is assumed that the pond level remained constant).

The demin through-put would remain approximately the same for the base case and for the IX case studies, as the RWB input would be decreased by the amount of IX product water generated. The slight increase in demand on demin water for the IX regenerations and reagent make-up (in total 1402m^3/mth), was assumed to have a negligible effect on the demin plant operations in terms of reagent usage. The RO plant through-put would increase by a factor of 6. In order to determine the RO plant reagent requirements for the two IX case studies, it was assumed that the quantity of reagents used is directly proportional to the through-put. It was further assumed that the RO plants would remove all of the metals and other impurities (including sodium and other cations and anions, such as sulphates) in the water stream passing through it.

Those reagents which were excluded from the original base case, according to the criteria established in section 3.3.2, were re-evaluated in terms of this scenario. The reagents associated with the operation of the RO plants were still below the cut-off limit of ≤0.03t/t Ni produced, and were thus excluded. The NaOH consumption did become significant for case study (b), however, and was thus included in the LCI (as shown in Table 9.7).

The mass of eluate was based on the metal content (refer to Table 9.5), as the solution volume was small. For case (a), the additional reagent consumptions due to the processing of the eluate were taken to be negligible as a first approximation, as the relative increase in metal production would be marginal (0.5% of the current total metal production). The additional reagent consumptions would also depend upon the eluate process routing employed. Similarly, the increase in jarosite production rates would be very small due to the Ca and Mg content in the eluate.

For case (b), the caustic required to precipitate the metals in the IX eluate (as $M(OH)_2$, where M denotes a divalent metal ion), was calculated from the metal ion concentrations given in Table 9.5. The stoichiometric NaOH requirement plus 10% was then used in the LCI. The consequent additional Na ion concentration in the effluent stream from the caustic precipitation filtrate was included in the Na purge calculations. In terms of crystallisation of the RO brine, it was assumed as a first approximation that all of the divalent metal ions which reported to the IX product water (shown in Table 9.5), as well as the ammonium, sulphate, and sodium ions present in the effluent (Table 9.1) and the additional sodium and sulphate ions from the effluent IX regenerations (and the sodium ions from the caustic eluate precipitation in case (b)) would be crystallised out.

The additional steam requirement for this was calculated from the assumption that 1.1tons of steam would be required to crystallise one ton of liquor (provided by a single effect evaporator) (the mass of liquor was estimated from the mass of anions and cations present plus 4500m^3 of water (approximately 15% of the RO input volume)). The subsequent increased inputs and outputs for the steam generation process were calculated as described in section 8.4. The additional steam vented by the BMR was taken as 50% of the extra steam input. The additional condensate return was then found by difference, and was subtracted from the required water input to the BMR process. The relative usage of the IX product water by the BMR process and the steam generation plant was calculated from the ratio of total water input to these two operations, and the remaining RWB water requirements were calculated by difference.

The increased electricity requirements for both case studies were calculated as discussed in 9.3.3. The additional general pumping requirements relate to three 11kW pumps, while four additional RO plant pumps would become operational (2 x

22kW, 5.5kW and 7.5kW). From this information, the additional kWh consumption per month was calculated, as given in Tables 9.6 and 9.7. This represents an increase of approximately 1% of the total BMR electricity consumption.

Errors were incurred in these mass balances due to the approximate nature of the preliminary proposal used, as well in the conversion of a number of the volume measurements to masses (the density was approximated to be that of water). The error was thus around 10-15%.

INPUTS				**OUTPUTS**		
Stream	**t/month**	**Source**		**Stream**	**t/month**	**Source**
Effluent pond balance:						
Rain	13189	Base case		Evaporation ex pond	912	Base case
Effluent ex steam gen.	850	Base case adjusted for inc. steam		Effluent to IX	27163	By difference
Effluent ex BMR	12716	Base case				
Recycle ex IX regeneration	1320	Proposal				
Sub-totals:	**28075**				**28075**	
Effluent IX:						
Effluent ex pond	27163	As above		Eluate to BMR	7.6	Calculated
H_2SO_4	48	Proposal		Recycle to pond	1320	Proposal
Water	1402	Proposal		Product water to BMR	8030	Calculated
				Product water to steam generation	19133	Calculated
Electricity (kWh)	64800	Calculated		Na purge to BMR	297	Calculated
Sub-totals:	**28613**				**28788**	
BMR:						
Eluate ex IX	7.6	As above		Metal products	7.6	As above
Na purge ex IX	297	As above		Ammonium sulphate (Na purge product)	297	As above
Steam for Na purge	5277	Calculated		Steam vented	2639	50% of extra steam
				Condensate returns	2638	By difference
Sub-totals:	**5582**				**5582**	

Table 9.6: Effluent IX case (a) additional inputs and outputs.

INPUTS				OUTPUTS		
Stream	**t/month**	**Source**		**Stream**	**t/month**	**Source**
Effluent pond balance:						
Rain	13189	Base case		Evaporation ex pond	912	Base case
Effluent ex steam gen.	850	Base case adjusted for inc. steam		Effluent to IX	27177	By difference
Effluent ex BMR	12730	Base case + caustic filtrate				
Recycle ex IX	1320	Proposal				
Sub-totals:	**28089**				**28089**	
Effluent IX:						
Effluent ex pond	27177	As above		Eluate to BMR	7.6	Calculated
H_2SO_4	48	Proposal		Recycle to pond	1320	Proposal
Water	1402	Proposal		Product water to BMR	8032	Calculated
NaOH	18	Proposal		Product water to steam generation	19145	Calculated
Electricity (kWh)	64800	Calculated		Na purge to BMR	297	Calculated
Sub-totals:	**28645**				**28802**	
BMR:						
Eluate ex IX	7.6	As above		Caustic metal precipitate	12.5	Calculated
Na purge ex IX	297	As above		Ammonium sulphate (Na purge product)	304	Calculated
Steam for Na purge	5285	Calculated		Steam vented	2643	50% of extra steam
NaOH	26	Calculated		Condensate returns	2642	By difference
				Caustic filtrate effluent	14	By difference
Sub-totals:	**5616**				**5616**	

Table 9.7: Effluent IX case (b) additional inputs and outputs.

REAGENT	Case (a)	Case (b)
Resin	2000ℓ/4 years	2000ℓ/4 years
NaOH	18t	Included
RO plant reagents:		
Flocon 100	840ℓ	840ℓ
Na metabisulphite	96kg	96kg
EDTA	240kg	240kg
HCℓ	36kg	36kg

Table 9.8: Additional reagents required for the effluent IX process options, which were excluded from the LCI.

The quantities are per month, unless otherwise indicated.

9.5) EVALUATION

The detailed environmental profiles thus derived for the two case studies are presented in Tables 9.9 and 9.10, while Table 9.11 and Figure 9.5 provide a comparison with the base case.

It is evident from these results, that the aquatic ecotoxicity and eutrophication impact scores decreased significantly when the effluent was treated by IX instead of being routed to Ergo, as the effluent contributed significantly to these categories in the base case. The water usage impact score was also reduced in line with the RWB water consumption. The other impact category scores increased slightly for the effluent IX case studies, however, due to the increase in sulphuric acid usage, and steam and electricity requirements. The increase for case (b) was slightly higher than that for case (a), due to the inclusion of NaOH in the LCI.

Impact category	TOTAL	BMR total	BMR process	O_2 from air decomposition	N_2 from air decomposition	H_2SO_4	HNO_3	Ammonia	H_2 total	H_2 produced	Natural gas delivered UK	Steam total	Steam generated	Coal, hard UK	SA elec	Effluent
GWP (kg CO_2)	**28666**	**2564**	0.00	352	167	299	38.5	1708	**1057**	888	169	**18541**	16199	2342	**6504**	**0.00**
Water in (kg)	**118936**	**45375**	9946	15567	7370	6860	147	5485	**918**	0.00	918	**59011**	27754	31256	**12190**	**1442**
Resource depletion (/year)	**64.4**	**14.9**	0.00	1.23	0.58	1.41	0.25	11.4	**11.9**	0.00	11.9	**31.3**	0.00	31.3	**6.27**	**0.00**
Acidification (kg SO_2)	**334**	**22.5**	0.00	2.21	1.05	7.57	0.27	11.4	**0.95**	0.00	0.95	**229**	224	4.33	**81.7**	**0.00**
Ecotoxicity (Aquatic m^3)	**1.64**	**0.03**	0.00	0.01	0.00	0.01	0.00	0.01	**0.02**	0.00	0.02	**0.81**	0.00	0.81	**0.78**	**0.00**
Ecotoxicity (Terrestrial m^3)	**2.51E-02**	**1.34E-02**	0.00E+00	3.85E-03	1.82E-03	3.34E-03	1.41E-04	4.22E-03	**1.21E-03**	0.00E+00	1.21E-03	**1.05E-02**	0.00E+00	1.05E-02	**8.96E-07**	**0.00E+00**
Eutrophication (kg PO_4)	**46.8**	**1.79**	0.00	0.10	0.05	0.07	0.04	1.53	**0.09**	0.00	0.09	**42.2**	33.4	8.75	**2.70**	**0.00**
Human Toxicity (kg/kg)	**434**	**32.8**	0.00	3.27	1.55	9.46	0.40	18.1	**1.61**	0.00	1.61	**261**	254	7.26	**138**	**0.00**
Ozone depletion (kg CFC 11)	**6.11E-04**	**3.38E-04**	0.00E+00	8.20E-05	3.88E-05	5.47E-05	3.57E-06	1.59E-04	**9.12E-05**	0.00E+00	9.12E-05	**1.82E-04**	0.00E+00	1.82E-04	**0.00E+00**	**0.00E+00**
Smog (kg ethene)	**12.7**	**2.44**	0.00	0.08	0.04	0.06	0.04	2.21	**0.13**	0.00	0.13	**0.88**	0.00	0.88	**9.25**	**0.00**
Smog (kg NO_x)	**288**	**8.02**	0.00	0.70	0.33	0.54	0.19	6.26	**0.59**	0.00	0.59	**259**	257	2.28	**20.5**	**0.00**

Table 9.9: Environmental profile for case (a) of the effluent IX treatment scenario (production of one ton of nickel).

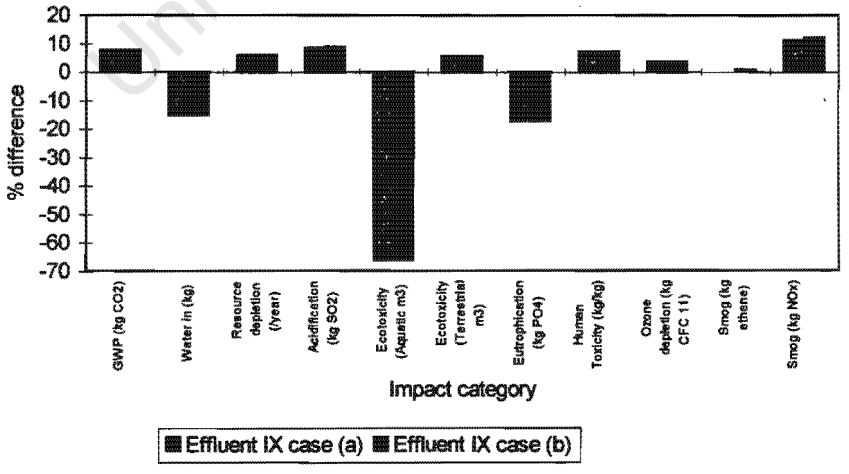
Impact category	TOTAL	BMR total	BMR process	O_2 from air decomposition	N_2 from air decomposition	H_2SO_4	HNO_3	Ammonia	H_2 total	H_2 produced	Natural gas delivered UK	Steam total	Steam generated	Coal, hard UK	SA elec	Effluent	NaOH
GWP (kg CO_2)	**28719**	**2564**	0.00	352	167	299	38.5	1708	**1057**	888	169	**18544**	16201	2342	**6504**	**0.00**	**50.7**
Water in (kg)	**119173**	**45369**	9940	15567	7370	6860	147	5485	**918**	0.00	918	**59012**	27750	31261	**12190**	**1444**	**240**
Resource depletion (/year)	**64.5**	**14.9**	0.00	1.23	0.58	1.41	0.25	11.4	**11.9**	0.00	11.9	**31.3**	0.00	31.3	**6.27**	**0.00**	**0.18**
Acidification (kg SO_2)	**335**	**22.5**	0.00	2.21	1.05	7.57	0.27	11.4	**0.95**	0.00	0.95	**229**	224	4.33	**81.7**	**0.00**	**1.08**
Ecotoxicity (Aquatic m^3)	**1.65**	**0.03**	0.00	0.01	0.00	0.01	0.00	0.01	**0.02**	0.00	0.02	**0.81**	0.00	0.81	**0.78**	**0.00**	**0.01**
Ecotoxicity (Terrestrial m^3)	**2.51E-02**	**1.34E-02**	0.00E+00	3.85E-03	1.82E-03	3.34E-03	1.41E-04	4.22E-03	**1.21E-03**	0.00E+00	1.21E-03	**1.05E-02**	0.00E+00	1.05E-02	**8.96E-07**	**0.00E+00**	**3.89E-05**
Eutrophication (kg PO_4)	**46.8**	**1.79**	0.00	0.10	0.05	0.07	0.04	1.53	**0.09**	0.00	0.09	**42.2**	33.4	8.75	**2.70**	**0.00**	**0.04**
Human Toxicity (kg/kg)	**434**	**32.8**	0.00	3.27	1.55	9.46	0.40	18.1	**1.61**	0.00	1.61	**261**	254	7.26	**138**	**0.00**	**0.81**
Ozone depletion (kg CFC 11)	**6.11E-04**	**3.38E-04**	0.00E+00	8.20E-05	3.88E-05	5.47E-05	3.57E-06	1.59E-04	**9.12E-05**	0.00E+00	9.12E-05	**1.82E-04**	0.00E+00	1.82E-04	**0.00E+00**	**0.00E+00**	**0.00E+00**
Smog (kg ethene)	**12.8**	**2.44**	0.00	0.08	0.04	0.06	0.04	2.21	**0.13**	0.00	0.13	**0.88**	0.00	0.88	**9.25**	**0.00**	**0.11**
Smog (kg NO_x)	**289**	**8.02**	0.00	0.70	0.33	0.54	0.19	6.26	**0.59**	0.00	0.59	**259**	257	2.28	**20.5**	**0.00**	**0.33**

Table 9.10: Environmental profile for case (b) of the effluent IX treatment scenario (for the production of one ton of nickel).

IMPACT CATEGORY	BASE CASE	EFFLUENT IX CASE (a)	CASE (a): % DIFFERENCE	EFFLUENT IX CASE (b)	CASE (b): % DIFFERENCE
GWP (kg CO_2)	26611	28666	7.7	28719	7.9
Water in (kg)	139401	118936	-15	119173	-15
Resource depletion (/year)	60.9	64.4	5.7	64.5	5.9
Acidification (kg SO_2)	308	334	8.4	335	8.8
Ecotoxicity (Aquatic m^3)	4.88	1.64	-66	1.65	-66
Ecotoxicity (Terrestrial m^3)	2.38E-02	2.51E-02	5.5	2.51E-02	5.5
Eutrophication (kg PO_4)	56.3	46.8	-17	46.8	-17
Human Toxicity (kg/kg)	406	434	6.9	434	6.9
Ozone depletion (kg CFC 11)	5.91E-04	6.11E-04	3.4	6.11E-04	3.4
Smog (kg ethene)	12.7	12.7	0	12.8	0.8
Smog (kg NO_x)	259	288	11	289	12

Table 9.11: Comparison of the base case environmental profile to those of the effluent IX case studies.

Figure 9.5: The percentage change in environmental profile scores for the effluent IX case studies as compared to the base case



9.6) DISCUSSION AND CONCLUSION

The advantage of re-processing the metal eluate to produce metal products is that it facilitates subsequent recycling, whereas the inclusion of the metals in ammonium sulphate may lead to their diffusion, upon use of the material as fertiliser. (Although the presence of small quantities of these metal ions in the fertiliser could serve as a source of essential trace elements for plants, seepage to groundwater or run-off to surface waters could occur).

Various other potential process options should also be evaluated. It is possible, for example, that instead of using "fresh" caustic for the metal eluate precipitation, spent reagent from either the IX or demin resin regeneration processes could be recycled for this purpose. This would reduce the environmental impacts associated with the production of the additional reagent and would reduce costs. Obviously, the efficiencies of the precipitation, and any spent reagent treatments (such as pre-concentration) would also have to be considered.

Indirect recycling of the metal eluate precipitate is another process option which should be evaluated. This would be achieved by returning the caustic precipitate to Mineral Processes for impurity removal, and then returning the metal content to the BMR as a component of the matte. In terms of the LCA boundaries already drawn (refer to Chapter 3), the environmental impacts associated with either direct (case (a)) or indirect processing would be the same, as the operations of Mineral Processes do not lie within the LCA boundary. A more detailed study regarding the environmental impacts associated with the processing of these solids at Mineral Processes would thus be necessary, in order to ensure that a trade-off does not occur, in that an improvement in waste treatment at the BMR does not lead to unaccounted negative environmental impacts elsewhere.

There is also the possibility that the metal eluate could be sold to other value-adding operations, such as the coinage industry, which should be investigated. In all cases, including those considered in the case studies, a cost analysis is another important component in the evaluation of the process options, especially with respect to capital equipment requirements. These costs will be offset by savings in terms of reduced RWB water consumptions and metal recoveries. Such cost analyses are to form part of subsequent feasibility studies.

Due to the change in effluent quality which has already occurred, as well as planned process changes which will further affect the effluent quality, it would be valuable to repeat the LCA at a later date with the new effluent variables. A more detailed study could also be done, in which the final fate of water treatment chemicals could be investigated, for example. (Although these chemicals would be present in the effluent at very low concentrations, they may cause significant environmental impacts (refer to section 4.4)).

It is evident from the two case studies investigated, that re-processing of effluent by IX would significantly reduce the potential aquatic ecotoxicity and eutrophication effects. In addition to this, a cost saving could be realised due to the reduction in RWB water consumption. Trade-offs were evident, however, in that a relatively small (<12%) increase in the other environmental impact categories occurred, due to additional reagent inputs and utility requirements.

In conclusion, the BMR of Impala Platinum Ltd is constantly striving to reduce wastage. This is evident from both the improvement in effluent water quality, as well as from the installation of effluent treatment facilities. It is important, however, that the broader environmental impacts (such as those associated with additional reagent and electricity usage) which are generally excluded from cursory assessments, are also considered, as they can influence the outcome of the assessment. In this scenario, the environmental model developed has been shown to be of value in this respect, in terms of the environmental assessment of waste disposal options.

Chapter 10: CONCLUSIONS AND RECOMMENDATIONS

The evaluation of environmental performance by means of a first-order life cycle assessment has been shown to be of use in the base metal refining industry, by means of the Impala Platinum Limited Base Metal Refinery case study. Monthly operating data from the plant was successfully compiled into life cycle inventories, from which relationships between operating conditions and environmental performance could be derived. One of the main findings was that the unit environmental impact scores decreased with increased nickel production in the range of nickel productions investigated. This economy of scale in the environmental sense was a consequence of the high fixed energy load of the BMR, which resulted in improved energy efficiencies at higher Ni production rates.

The environmental model developed in this project was useful in the identification of major contributors to the environmental profile scores. The base case LCA results indicated that the steam generation plant and the use of electricity were the two areas of greatest potential environmental impact, thus environmental improvement efforts should be focused on them. It is recommended that monitoring of emissions from the boilers be introduced in order to aid quantification of impacts. The quality of the coal used for steam generation should also be maintained in order to minimise impacts due to inferior coal usage. Means of reducing wastage of steam (and therefore energy) by steam losses and venting, as well as improving steam usage efficiencies, should be further studied. The environmental impacts associated with other types of boilers (such as gas-fired boilers) and their relative costs could also be investigated as alternatives to coal combustion for steam generation purposes.

The impacts associated with electricity consumption are similar to those relating to the steam generation plant, as electricity is produced in Gauteng, South Africa by coal burning. The most obvious way to reduce these potential impacts would be to minimise electricity consumption by the BMR, which would have the added benefit of reducing costs. Impala Platinum Refineries has previously embarked on a successful water saving programme (section 4.6.2), and a similar campaign to reduce electricity wastage could be initiated. As a start, a more comprehensive metering system could be introduced to aid in the identification of areas of improvement. A small increase in electrical efficiency by the copper winning circuit, for example, would result in a significant decrease in electricity consumption, due to

the large electricity usage by this section. In evaluating environmental improvements, the economic factors associated with them would also need to be addressed.

The LCA model developed was successfully used to perform preliminary evaluations of the environmental performance of different process options, within the limitations of the assumptions employed in each scenario. The environmental impacts associated with nickel sulphate processing were compared to those of processing matte (plus a small quantity of cobalt nitrate). Each of the unit environmental impact scores were lower for the production of nickel from nickel sulphate, due to reduced electricity and reagent requirements (milling, leaching, and copper electrowinning were not necessary for the processing of this material).

The effects of an increase in cobalt (and nickel) production on the environmental profile was investigated. This would be due to the processing of a new type of material and the consequent introduction of cobalt solvent extraction technology. The trend of decreasing unit environmental impact scores with increased nickel production was again followed. The electricity consumption per ton of nickel produced decreased significantly, due to an increase in the nickel to copper production ratio (copper winning is an energy-intensive process). It must be noted that this was a preliminary assessment and further details regarding the use of the organic solvent (such as quantities reporting to the effluent) should be included in a more comprehensive study.

A variation in waste disposal options was then assessed. A decrease in water consumption by means of treating and then recycling effluent by ion exchange was found to also significantly decrease potential aquatic ecotoxicity and eutrophication impacts, compared to those associated with the current use of the effluent in slimes dam recovery operations. A trade-off was evident, however, as the other impact scores increased slightly due to increased reagent and utility usage. It must be noted that the effluent quality was not a function of production volumes, but rather due to a variation in plant operation. This illustrates the importance of training staff in the environmental aspects of their actions.

In terms of future work, it would be advantageous to extend the boundaries used in this first-order LCA to include the upstream operations of Mineral Processes, and the Precious Metals Refinery downstream. In this manner, an environmental model could be developed for Impala Platinum as a whole, which would serve as a useful

tool in corporate decision making. Ultimately, details on the use, recycling and final disposal of the products should be included, although due to the diffuse use of Impala's products this is not seen to be an achievable goal at present. With respect to the BMR itself, the introduction of an air emission monitoring programme and the subsequent inclusion of these results in the LCA model presented in this thesis, could provide some interesting results and indicate other areas of potential improvement, whilst completing the current waste monitoring strategy.

In conclusion, it is evident that such a first-order life cycle assessment is potentially useful as an environmental support tool in the base metal refining industry, in terms of establishing a baseline of environmental performance; for the identification of areas of greatest potential environmental improvement; and for the comparison of the environmental performance of different process options.

Due to the fact that certain areas of the LCA methodology are presently in the developmental stages (such as the determination of classification factors for human toxicity, and the development of regional normalisation factors), and that the software currently available does not contain very comprehensive databases for a number of reagents commonly used in the base metal refining industry, it may not be feasible to utilise LCA methodology on a routine basis by this sector of industry at present.

The possible future enactment of a pollutant register in South Africa (similar to the National Pollutant Inventory in Canada) would aid in the development of national and regional normalisation factors for some of the impact categories. This is because the measurement of emissions would become compulsory and the data would be centrally recorded, which would facilitate retrieval and subsequent integration of emissions by area or industry. This information would be useful in the determination of normalisation factors for the greenhouse effect, for example.

The current development of standards for conducting life cycle assessments as part of the ISO 14000 series should also iron out the methodology shortfalls and thus make implementation of LCA into environmental management systems more feasible. This will lead to more LCA studies being performed, and consequently the databases will be expanded. It thus appears only a matter of time before LCA becomes an integral feature in the determination of environmental performance by industry.

REFERENCES:

Allen, H.E., Importance of speciation of metals in natural waters and soils to risk assessment, Proceedings of the International Workshop on Risk Assessment of Metals and Their Inorganic Compounds, Angers, France, November 1996, pp 141-158.

Anthony, T., and Flett, D.S., Nickel processing technology: A review, *Minerals Industry International*, January 1997, pp 27-41.

Austin, G.T., Shreve's Chemical Process Industries, 5th ed, McGraw-Hill Inc., Singapore, 1984.

Ayres, R.U., and Ayres, L.W., Industrial Ecology - Towards closing the materials cycle, University Press, UK, 1996.

Ayres, R.U., and Simonis, U.E. (eds), Industrial Metabolism- Restructuring for Sustainable Development, United Nations University Press, New York, 1994.

Azapagic, A., Life cycle assessment: a tool for innovation and improved environmental performance, Proceedings of the International Conference on Technology Policy and Innovation, Macau, 1997.

Barnthouse, *et al*, (eds), Evolution and development of the conceptual framework and methodology of life-cycle impact assessment, Addendum to Life-Cycle Impact Assessment: The State-of-the-Art, 2nd ed, SETAC, 1998.

Bautista, R.G., The solvent extraction of nickel, cobalt and their associated metals, Proceedings of the Paul E. Queneau International Symposium on Extractive Metallurgy of Copper, Nickel and Cobalt, Volume I: Fundamental Aspects, Reddy R.G. and Weizenbach, R.N., (eds), the Minerals, Metals and Materials Society, 1993, pp 827-852.

Bayer, Lewatit Purifies Water, Brochure, 1997.

Boldt, J.R., The Winning of Nickel Its Geology, Mining, and Extractive Metallurgy, Ed: Queneau, P., Methuen and Co. Ltd, Canada, 1967.

Broadhurst, J.L., Composition and Stability of the Jarosite Plant Residue Produced at Impala Refineries, Confidential Report no. 92/135F, 1992.

Brugman, C.F., and Kerfoot, D.G., Treatment of Nickel-Copper Matte at Western Platinum by the Sherritt Acid Leach Process, Proceedings of the 25th Annual Conference of Metallurgists, Toronto, Ontario, August 1986, pp 512-531.

Burkin, A.R., Extractive Metallurgy of Nickel: Hydrometallurgy of nickel sulphides, A.R., John Wiley and Sons, UK, 1987, pp 98-146.

Burks, S.F., Cobalt in Africa: New developments, Colloquium on Trends in Base Metals Smelting and Refining, The South African Institute of Mining and Metallurgy, 1997.

Chematron Products (Pty) Ltd, Proposal: Impala Heavy Metals Recovery Ion Exchanger, July 1998.

Christiansen, K., in Weidema, B.P., Chapter 1, 1993

Clift, R., Pollution and waste management I: Cradle-to-grave analysis, *Science in Parliament*, **50**, (3), June, 1993a, pp 29-32.

Clift, R., Life cycle assessment and ecolabelling, *J. Cleaner Prod.*, **1**, (3-4), 1993b, pp 155-159.

Conard, B.R., Is "nickel" safe? A toxicology primer, Proceedings of the Nickel-Cobalt 97 International Symposium, Volume III, Sudbury, Ontario, August 1997.

Copper Development Association, Copper In Human Health, as presented at http://environment.copper.org/uk/uk96.htm, 1998.

Cowell, S.J., Hogan, S., and Clift, R., LCANET Theme Report: Positioning and applications of LCA, 1997, obtained from http://www.leidenuniv.nl/interfac/cml/lcanet/ftheme1.htm.

Crittenden, B., Environmental life-cycle analysis: a tool for waste minimisation, *IChemE Environmental Protection Bulletin*, **032**, 1994, pp 5-11.

Curcio, L., President of NiPERA, Letter to the National Toxicology Programme Director (Kenneth Olden), 9 December 1998.

Cutler, P., Nickel: Friend or foe?, *Minerals Industry International*, January 1997, pp 21-25.

Cytec Industries, Brochure entitled: Cyanex Extractants, 1996.

Daae, E., and Clift, R., A life cycle assessment of the implications of paper use and recycling, Proceedings of the 1994 IChemE Research Event, London, January 1994, pp 305-307.

Denison R.A., in Weidema, B.P., Chapter 4: Towards a code of ethical conduct for life cycle assessments, 1993.

Dennis, A., Environmental Officer, Ergo, Private communication, 1998.

Department of Environmental Affairs and Tourism and the Department of Water Affairs and Forestry (S.A.), Discussion document towards a White Paper on Integrated Pollution Control and Waste Management, May 1997.

Dethlefsen, V., Jackson, T., and Taylor, P., in Jackson, T., Chapter 3: The Precautionary Principle, 1993.

De Waal, D.J.A., Presentation on Impala Platinum's Enhanced Precious Metal Refinery, PML, 1997.

Dutrizac, J.E., Jarosite-type compounds and their application in the metallurgical industry, Hydrometallurgy Research, Development and Plant Practice, Proceedings of the 3rd International Symposium on Hydrometallurgy, Atlanta, Georgia, March 1983, pp 531-551.

Elkington, J., The uses and abuses of life cycle analyses by non-governmental organizations, *J. Cleaner Prod.*, **1**, (3-4), 1993, pp 151-153.

Ensor, L., Three levies proposed to raise funds, Business Day, Thursday, June 4 1998, p 5.

Eskom Annual Environmental Report, http://www.eskom.co.za, 1997.

Fava, J.A., Consoli, F., and Denison, R.A., in Weidema, B.P., Chapter 2, 1993.

Feather, A.M., and Cole, P.M., The separation of cobalt from nickel ammonium sulphate solution by solvent extraction, International Solvent Extraction Conference, Melbourne, 1996.

Finnveden, G., and Lindfors, L., Data quality of life cycle inventory data- rules of thumb, *Int. J. LCA,* **3**, (2), 1998, pp 65-66.

Flett, D.S., Review of solvent extraction testwork and plant design for Impala Platinum Ltd, Confidential report, 1997.

Flett, D.S., Chemistry of nickel-cobalt separation, in Burkin, A.R., 1987, pp 76-97.

Foundation for Research Development, http://www.frd.ac.za, 1998.

Fox, M.H., *et al*, Comparison of some aspects of the performance of a Bateman pulse column and conventional box-type mixer/settlers, Proceedings of Alta 1998 Nickel/cobalt pressure leaching and hydrometallurgy forum, Perth, Australia, May 1998.

Gaylard, P.G., Private communication, 1998a.

Gaylard, P.G., Private communication, 1998b.

Geldenhuys, H., Environmental Manager, Ergo, Private communication, 1998.

Gombault, E., Regional Manager, Landfill Management, Private communication, 1998.

Graedel, T.E., Prioritizing Impacts: The second stage of life cycle assessment, IEEE, 1994, pp 89-93.

Guinée, J.B. (final editor), Environmental Life Cycle Assessment Backgrounds Draft document, http://www.leidenuniv.nl/interfac/cml/lca2, October 1998.

Guinée, J.B., *et al*, USES: Uniform System for the Evaluation of Substances, *Int. J. LCA*, **1**, (3), 1996, pp 133-138.

Guinée, J.B., Review of classification and characterisation methodologies, in Integrating Impact Assessment into LCA, Udo de Haes, H.A. *et al* (eds), SETAC, Brussels, 1994, pp 51-60.

Guinée, J.B., Heijungs, R., Udo de Haes, H.A., and Huppes, G., Quantitative life cycle assessment of products, 2. Classification, valuation and improvement analysis, *J. Cleaner Prod.*, **1**, (2), 1993a, pp 81-91.

Guinée, J.B., Udo de Haes, H.A., and Huppes, G., Quantitative life cycle assessment of products, 1. Goal definition and inventory, *J. Cleaner Prod.*, **1**, (1), 1993b, pp 3-13.

Guinée, J.B., and Heijungs, R., A proposal for the classification of toxic substances within the framework of life cycle assessment of products, *Chemosphere*, **26**, (10), 1993c, pp 1925-1944.

Harrison, R.M., (Ed), Pollution: Causes, Effects, and Control, 2nd edition, The Royal Society of Chemistry, Great Britain, 1990.

Hawkins, M., Steel industry: Cobalt, *Metals and Minerals Annual Review*, 1997.

Hayes, E.J., Steel industry: Nickel, *Metals and Minerals Annual Review*, 1997, pp 56-57.

Heijungs, R., and Frischknecht, R., A special view on the nature of the allocation problem, *Int. J. LCA*, **3**, (5), 1998, pp 321-332.

Heijungs, R. (final editor), Environmental Life Cycle Assessment of Products- Guide, Centre of Environmental Science, Leiden, 1992a.

Heijungs, R. (final editor), Environmental Life Cycle Assessment of Products- Backgrounds, Centre of Environmental Science, Leiden, 1992b.

Hirschhorn, J, Jackson, T., and Baas, L., Chapter 7: Towards Prevention, in Jackson, 1993.

Hofirek, Z., and Badcock, R.F.W., Selection of alternative methods of sulphur removal and disposal at Rustenburg Base Metal Refiners, Colloquium on Trends in Base Metals Smelting and Refining, The South African Institute of Mining and Metallurgy, 1997.

Hofirek, Z., and Kerfoot, D.G.E., The chemistry of the nickel-copper matte leach and its application to process control optimisation, *Hydrometallurgy*, **29**, 1992, pp 357-381.

Hunt, R.G., *et al*, Case studies examining LCA streamlining techniques, *Int. J. LCA*, **3**, (1), 1998, pp 36-42.

ICI, Extracts from the 1997 Environmental Report: http://www.ici.com/safety.htm, 1997a.

ICI, Environmental Burden: The ICI Approach, 2nd edition, 1997b, obtained from http://www.ici.com/download/index.htm.

Impala Nickel Business Development Unit, Internal Impala document: FEMS mass balance generated in Metsim, 1996.

Impala Platinum Limited Refineries, Environmental Policy Statement, 26 March 1998.

Impala Platinum Limited, Induction Manual for the Refineries, 1989.

Impala Platinum Limited, Gencor publication for the visit by the Council of Mining and Metallurgical Institutions, May, 1982.

Impala Platinum Limited, Advertising brochure, approximately 1980.

Inami, T., Toyabe, K., and Kanai, T., Cobalt refining process at Sumitomo Niihama Nickel Refinery, *Metallurgical Review of MMIJ*, **1**, (2), 1984, pp 125-137.

Ireland, D.A., The first ten years of operations at Impala Platinum Limited, Proceedings of the Third Conference on Precious Metals, The International Precious Metals Institute, Inc., Chicago, May 1979.

ISO, Environmental management- Life cycle assessment- Goal and scope definition and inventory analysis, International standard ISO 14041, Switzerland, 1998.

Jackson, T. (ed), Clean Production Strategies- Developing Preventive Environmental Management in the Industrial Economy, Lewis Publishers, USA, 1993.

Jacobs, J.J., *et al*, Nickel and Cobalt Extraction Using Organic Compounds, Pergamon Press, Great Britain, 1985.

Jacobs, M., The Green Economy: Environment, Sustainable Development and the Politics of the Future, Pluto Press, London, 1991.

Jönson, G., LCA- A Tool for Measuring Environmental Performance, Pira, UK, 1996, pp 50-53.

Keoleian, G.A., The application of life cycle assessment to design, *J. Cleaner Prod.*, **1**, (3-4), 1993, pp 143-149.

Knuutila, K., *et al*, New nickel process increasing production at Outokumpu Harjavalta Metals Oy, Finland, Proceedings of the Alta 1997 Nickel/cobalt Pressure Leaching and Hydrometallurgy Forum, 1997.

Kohga, T., *et al*, Cobalt nodules, *Cobalt News*, **3**, 1996, pp 6-9.

Kotzian, R., and Wakeman, R.J., Copper ion removal from aqueous solutions using lecithin enhanced ultrafiltration, Proceedings of the 1997 IChemE Jubilee Research Event, 1997, pp 1025-1028.

Lang, J.D., Armstrong, R.W., and Murphy, M.W., Application of the Isa Process to copper electrowinning and refining, Colloquium on Trends in Base Metals Smelting and Refining, The South African Institute of Mining and Metallurgy, Randburg, April 1997.

Mackiw, V.N., and Veltman, H., Recent Advances in Sherritt's Pressure Hydrometallurgical Technology, *Engineering and Mining Journal*, **182**, (12), 1982, pp 76-107.

Makwana, M., Sherritt International Corporation, Private communication with T. Spandiel, Impala, September 1996.

McDowell, G.M., and Spandiel, T., Nickel Copper Refinery Base Model: Introduction and Documentation of the Impala NCR METSIM model, Internal Impala Report, April 1996.

McKean, B., NiDI, Private communication, 05 June 1998.

Middleton, B., Water audit - the resource, the future, some solutions, *Water, Sewage and Effluent*, **18**, (1), March/April 1998, pp 20-22.

Mongkolsuk, S., *et al*, (eds), *CRI/ICEIT Newsletter*, (Chulabhorn Research Institute, International Centre for Environmental and Industrial Toxicology), **8**, (3), July 1998, p 4.

Montgomery, G.W.G., and Holohan, T.N., Development and design of the Hartley Platinum Base Metal Refinery flowsheet, Colloquium on Trends in Base Metals Smelting and Refining, The South African Institute of Mining and Metallurgy, Randburg, April 1997.

Morris, L., Falconbridge, Private communication, 30 June, 1998a.

Morris, L., Falconbridge, Private communication, 07 July, 1998b.

NiPERA (Nickel Producers Environmental Research Association), http://www.nipera.org, 1999.

NiPERA (Nickel Producers Environmental Research Association), Evaluation of Respiratory Carcinogenicity of Nickel and Nickel Compounds, October, 1998.

Notten, P.J., The Role of Life Cycle Assessment in Achieving Effective Environmental Management in Coal-fired Power Generation, PhD thesis (in progress), Department of Chemical Engineering, UCT, 1998.

Noyes, R., Pollution Prevention Technology Handbook, Noyes Publications, USA, 1993.

Oller, A., NiPERA, Private communication, 18 September 1998a.

Oller, A., NiPERA, Private communication, 08 October 1998b.

Oller, A., NiPERA, Private communication, 11 October 1998c.

Outokumpu Harjavalta Metals Oy, Company brochure, 1995.

Outokumpu Harjavalta Metals Oy, Company brochure, 1993.

Owens, J.W., Life-cycle assessment: Constraints on moving from Inventory to Impact Assessment, *Journal of Industrial Ecology*, **1**, (1), 1997a, pp 37-49.

Owens, J.W., Life-cycle assessment in relation to risk assessment: an evolving perspective, *Risk Analysis*, **17**, (3), 1997b, pp 359-365.

Owens, J.W., LCA impact assessment categories: Technical feasibility and accuracy, *Int. J. LCA*, 1, (3), 1996, pp 151-158.

Perriman, R.J., Special Appendix: A summary of SETAC guidelines for life cycle assessment, *J. Cleaner Prod.*, **1**, (3-4), 1993, pp 209-212.

Pira International, PEMS version 4 User Manual, UK, March 1998.

Plasket, R.P., and Dunn, G.M., Iron rejection and impurity removal from nickel leach liquor at Impala Platinum Limited, Proceedings of the Symposium on Iron Control in Hydrometallurgy, Metallurgical Society of C.I.M., Toronto, Canada, October 1986a, pp 695-718.

Plasket, R.P., and Dunn, G.M., Commissioning experiences in the cobalt plant at Impala Platinum Ltd., *Minerals and Metallurgical Processing*, February, 1986b, pp 7-14.

Plasket, R.P., and Romanchuk, S., Recovery of nickel and copper from high grade matte at Impala Platinum by the Sherritt Process, *Hydrometallurgy*, **3**, (2), 1978, pp 135-151.

Powlesland, C., Environmental assessment: the challenge for computer aided process engineering, Proceedings on the 4th European Symposium on Computer Aided Process Engineering ESCAPE 4, 1994, pp 487-494.

Preston, J.S., Solvent extraction of cobalt and nickel by organo-phosphorus acids I. Comparison of phosphoric, phosphonic and phosphinic acid systems, *Hydrometallurgy*, **9**, 1982, pp 115-133.

Rademan, J.A.M., An investigation of the kinetic behaviour of the cementation of copper with Ni-Cu matte, Colloquium on Trends in Base Metals Smelting and Refining, The South African Institute of Mining and Metallurgy, 1997.

Ralph, S.J., Private communication, 1998.

Ralph, S.J., Presentation at Impala Process Review meeting, 1998b.

Reagan, K., NiPERA toxicologist specialising in ecotoxicity, Private communication, 6 April 1999.

Reuter, M.A., *et al*, Synthesis of processes for the production of environmentally clean zinc, *Minerals Engineering*, **8**, (1/2), 1995, pp 201-219.

Reynolds, C.B.J., Environmental Manager, Impala Platinum Ltd Refineries, 1998.

Rickelton, W.A., Flett, D.S., and West, D.W., Cobalt-nickel separation by solvent extraction with bis(2,4,4 trimethyl pentyl)phosphinic acid, *Solvent and Ion Exchange*, **2**, (6), 1984, pp 815-838.

Sasol, Hydrogen Rich Gas Specification Sheet, 1998.

Searle, P., Strategic issues for cobalt, *Cobalt News*, **2**, 1997, pp 7-10.

SETAC, Guidelines for Life Cycle Assessments, "A code of practice", August, 1993.

Simons, C.S., The Production of Nickel: Extractive metallurgy- past, present, and future, Proceedings of the 117th Annual Meeting of The Metallurgical Society, Phoenix, Arizona, January 1988.

Skeaff, J., and King, P., Development of data on the reaction kinetics of nickel metal and nickel oxide in aqueous media for hazard identification, Final report by the Mining and Mineral Sciences Laboratories (MMSL), Canada, 1998.

Smit, J.J., The extraction of nickel with the use of supported liquid membranes (SLM), Report to the Water Research Commission by the Department of Chemical Engineering Potchefstroom University for CHE, WRC Report No. 617/1/97, 1997.

Sørensen, B., The role of life-cycle analysis in risk assessment, *Int. J. Environment and Pollution*, **6**, (4-6), 1996, pp 729-746.

Spandiel, T., The chemistry of the Impala base metal refining operations and its application to modelling and simulation, Internal Impala discussion document, 1997.

Stefanis, S.K., Livingston, A.G., and Pistikopoulos, E.N., A framework for minimizing environmental impact of industrial processes, Proceedings from the 1995 IChemE Research event, Edinburgh, January 1995, pp 164-166.

Stensholt, E.O., Zachariasen, H., and Lund, J.H., The Flaconbridge chlorine leach process, Proceedings of the Institution of Mining and Metallurgy's Extraction Metallurgy Symposium, London, 1985, pp 377-397.

Stewart, M., and Petrie, J., Life cycle assessment as a tool, *Mining and Environmental Management*, June 1997, pp 10-13.

Stewart, M., and Petrie, J., Report on The Waste Generation Potential of the South African minerals processing Industry, July, 1996a.

Stewart, M., and Petrie, J.G., Life cycle assessment for process design- the case of minerals processing, in Clean Technology for the Mining Industry, Sanchez, M.A. *et al* (eds), University of Concepcion, 1996b.

Stewart, M., and Petrie, J., Addressing limitations of environmental impact assessment using life cycle assessment, IAIA SA (International Association of Impact Assessment, South Africa), Conference Proceedings, Cape Town, South Africa, 1996c.

Stewart, M., and Petrie, J., Design for pollution prevention in minerals processing- a life cycle assessment perspective, Presented at CIM, Montreal, Canada, 1996d.

Suetsuna, A., *et al*, Sumitomo's new process for nickel and cobalt recovery from sulfide mixture, The Metallurgical Society of AIME, TMS Paper A80-2, 1980.

Technology Sciences Group Incorporated, Environmental Risk Assessment for Nickel in the European Union Based on EUSES Modelling and the Technical Guidance Document for New and Existing Substances, Final Report, January 1998.

Thompson, M., Major metals: Copper, aluminium, zinc, lead and tin, *Metals and Minerals Annual Review*, 1997, pp 33-38.

Udo de Haes, H.A., Applications of life cycle assessment: expectations, drawbacks and perspectives, *J. Cleaner Prod.*, **1**, (3-4), 1993a, pp 131-137.

Udo de Haes, H.A. and Huppes, G., Life cycle assessment and its applications, *J. Cleaner Prod.*, **1**, (3-4), 1993b, pp 201-202.

UNEP IE/PAC (United Nations Environment Programme: Industry and Environment Programme Activity Centre), Technical Report No. 15, Environmental Management of Nickel Production - A technical guide, United Nations Publication, 1993.

Unilever, http://www.unilever.com, 1999.

Union Minière, Annual Report 1996.

US EPA (Environmental Protection Agency), Risk Assessment Forum, Proposed Guidelines for Ecological Risk Assessment, EPA/630/R-95/002B, Washington D.C., August 1996.

Van der Venter, E.G., Confidential Impala Technical Report: Hydrogen Plants, August 1993.

Van der Vyver, The Minor Metals Overview, Republic of South Africa Department of Mineral and Energy Affairs: Minerals Bureau, 1993.

Van Graan, S.J., and Fourie, E.T., Resources of the Platinum-Group Metals and Associated Nickel, Copper and Cobalt of the Bushveld Complex, Republic of South Africa Department of Mineral and Energy Affairs, Minerals Bureau, 1992.

Veltman, H., and Weir, D.R., Sherritt Gordon's pressure leaching technology- its industrial application, Proceedings of the Hydrometallurgical Conference, Manchester, June 1981.

Vigon, B. (ed), *LCA News*, SETAC Foundation for Environmental Education, **18**, (3), May, 1998a.

Vigon, B. (ed), *LCA News*, SETAC Foundation for Environmental Education, **18**, (2), March, 1998b.

Vigon, B. (ed), *LCA News*, SETAC Foundation for Environmental Education, **18**, (1), January, 1998c.

Vigon, B. (ed), *LCA News*, SETAC Foundation for Environmental Education, **18**, (4), July, 1998d.

Vigon, B. (ed), *LCA News*, SETAC Foundation for Environmental Education, **17**, (3), May, 1997a.

Vigon, B. (ed), *LCA News*, SETAC Foundation for Environmental Education, **17**, (5), September, 1997b.

Vigon, B. (ed), *LCA News*, SETAC Foundation for Environmental Education, **17**, (6), November, 1997c.

Vigon, B. (ed), *LCA News*, SETAC Foundation for Environmental Education, **17**, (1), January, 1997d.

Vinnicombe, D.A., Wadley, S., and Buckley, C.A., Recycling of water and chemicals from ion exchange regeneration effluents, Proceedings of the South African Institute of Chemical Engineering Conference, 1991.

Volkwein, S., and Klöpffer, W., The valuation step within LCA. Part I: General principles, *Int. J. LCA*, **1**, (1) 1996a, pp 36-39.

Volkwein, S., Gihr, R., and Klöpffer, W., The valuation step within LCA. Part II: A formalized method of prioritization by expert panels, *Int. J. LCA*, **1**, (4) 1996b, pp 182-192.

Von Blottnitz, H., Development and Assessment of a Hydrometallurgical Process to Treat Chromium-Containing Dusts, Masters thesis, University of Cape Town, 1994.

Walker, A.G., and Burks, S.F., Nickel Copper Refinery Expansion Project: Pre-feasibility study report for the option to toll treat mixed sulphides from a nickel project in Asia, Bateman and Titaco, August 1996.

Watson, W., and Golding, B., Weighing up the risks, *Chemistry in Britain*, July 1998, pp 45-48.

Weidema, B.P., Environmental Assessment of Products- A textbook on life cycle assessment (2nd edition): Chapter 5: Quality criteria for product life cycle assessments, The Finnish Association of Graduate Engineers TEK, Finland, 1993.

World Commission on the Environment and Development, Our Common Future, Oxford University Press, 1987.

Xun, F., and Golding, J.A., Solvent extraction of cobalt and nickel in bis(2,4,4-trimethylpentyl)phosphinic acid, "Cyanex-272", *Solvent extraction and ion exchange*, **5**, (2), 1987, pp 205-226.

Yawili, N. (Chairman), Environmental update and current topics, *Cobalt News*, **4**, 1996, pp 7-8.

APPENDIX 1

MONTHLY LIFE CYCLE INVENTORIES
(PEMS INPUT DATA).

A1 (i): AVERAGE BMR PROCESS DATA: 1997

NOTE: All values are in t/mth, unless otherwise stated.

	01/97	02/97	03/97	04/97	05/97	06/97	07/97
INPUTS							
Raw materials							
Impala matte	1134	1610	1720	1277	1555	1298	1407
Other toll ref.	214	5	149	469	209	43	6
Ni sulphate	967	1192	1017	1533	1179	1177	1087
Co nitrate	0.0	82.0	40.1	42.9	84.7	133.5	136.3
Liquid reagents							
H_2SO_4 (kg)	1031317	1057246	1156867	1276370	1275424	1032800	1109857
HNO_3 (kg)	50460	79280	34580	91720	86940	50620	51620
Ammonia (kg)	893600	868500	888296	1094900	1040200	822350	808000
Gaseous reagents							
Oxygen (kg)	1270960	1292760	1316922	1156146	1097616	928342	929184
N_2	476	496	508	510	511	476	680
Inter-unit flows							
Steam	34383	35042	36399	37851	37854	37350	34522
Hydrogen used	68.0	80.4	81.6	89.0	91.8	92.3	99.5
CO_2 used	150	163	174	185	195	197	200
Standard flows							
Water	15116	16697	17334	15723	16316	14129	18270
TOTAL INPUTS	55754	58664	60820	61298	61496	57730	59307
OUTPUTS							
Main product							
Gross Ni produced	**950.0**	**916.0**	**1132.0**	**1356.0**	**1148.9**	**955.0**	**920.0**
Sintered Ni (A)	560.0	590.0	770.0	850.0	720.0	690.0	850.0
By-products							
Cu cathode	379	401	477	451	404	384	339
Co powder	8.00	8.00	10.50	5.80	10.80	7.30	7.50
Ammonium sulphate	2736	2643	2572	2424	2323	2812	2671
Se/Te solids	2.88	2.88	2.88	2.88	2.88	2.88	2.88
PGM concentrate	2.63	2.85	3.16	2.71	2.73	2.98	2.39
PGM solution	18.3	18.3	20.8	6.5	20.7	8.6	11.2
Wastes							
Jarosite	60.9	61.4	60.4	78.2	75.4	60.2	64.8
Effluent	23244	1691	13463	11537	9051	22373	12104
Standard flows							
Steam vented	18187	18147	19837	21398	24816	18746	18267
Cooling water losses	13336	13630	12805	13939	13012	12720	13640
N2 vented	476	496	508	510	511	476	680
Other open loop flows							
Demin to PMR	692	901	672	579	767	757	1124
Water to sewer	7713	7151	7018	6523	4866	6554	6211
TOTAL OUTPUTS	67806	46069	58582	58813	57011	65859	56045
INPUTS-OUTPUTS	-12051	12595	2238	2485	4485	-8129	3262
% ERROR	-21.6	21.5	3.7	4.1	7.3	-14.1	5.5
ENERGY INPUT							
Electricity (kWh)	6321960	6527342	6589871	7460092	6517336	6034995	6766098

A1 (ii): AVERAGE BMR PROCESS DATA: 1996

NOTE: All values are in t/mth, unless otherwise stated.
Average liquid reagent and oxygen values used from 01/96 to 06/96, inclusive.

	01/96	02/96	03/96	04/96	05/96	06/96	07/96
INPUTS							
Raw materials							
Impala matte	1532	1552	1506	1148	1560	1463	1443
Other toll ref.	32	0	0	0	0	104	8
Ni sulphate	830	1127	1323	883	1280	1582	1170
Co nitrate	22	140	148	124	101	130	112
Liquid reagents							
H_2SO_4 (kg)	1121086	1121086	1121086	1121086	1121086	1121086	984941
HNO_3 (kg)	60838	60838	60838	60838	60838	60838	48480
Ammonia (kg)	943182	943182	943182	943182	943182	943182	840900
Gaseous reagents							
Oxygen (kg)	1176411	1176411	1176411	1176411	1176411	1176411	1012532
N_2	525	606	764	561	419	497	1053
Inter-unit flows							
Steam	29715	31166	28286	28094	29678	30202	30254
Hydrogen used	57.6	72.3	74.0	46.4	67.0	65.3	58.2
CO_2 used	128	156	151	113	140	140	119
Standard flows							
Water	20871	24321	19204	20279	21158	18581	14452
TOTAL INPUTS	57015	62442	54757	54549	57704	56066	51556
OUTPUTS							
Main product							
Gross Ni produced	**934.0**	**1100.0**	**959.5**	**808.7**	**694.0**	**1045.0**	**1197.0**
Sintered Ni (A)	700.0	798.0	898.5	500.7	130.0	534.7	900.0
By-products							
Cu cathode	470	468	480	365	449	383	424
Co powder	8.00	8.00	7.90	6.80	6.00	4.40	6.40
Ammonium sulphate	2401	2875	3161	2774	2554	2541	2452
Se/Te solids	2.88	2.88	2.88	2.88	2.88	2.88	2.88
PGM concentrate	0.00	0.00	2.90	2.87	3.30	2.83	2.14
PGM solution	3.8	48.0	60.3	38.0	41.3	41.7	17.2
Wastes							
Jarosite	60.8	85.9	50.8	44.0	57.4	56.9	33.2
Effluent	309	-4113	4932	6169	8532	14398	10804
Standard flows							
Steam vented	13844	14193	14212	13752	12430	12344	13203
Cooling water losses	10300	12515	10050	11111	11977	9933	8863
N2 vented	525	606	764	561	419	497	1053
Other open loop flows							
Demin to PMR	425	662	444	592	762	573	732
Water to sewer	7499	8338	8532	6835	6101	5525	6272
TOTAL OUTPUTS	36782	36789	43659	43062	44029	47348	45062
INPUTS-OUTPUTS	20232	25653	11098	11487	13675	8718	6495
% ERROR	35.5	41.1	20.3	21.1	23.7	15.5	12.6
ENERGY INPUT							
Electricity (kWh)	6408819	6782063	6094588	5971357	6600427	6261809	6165971

A1 (ii): AVERAGE BMR PROCESS DATA: 1996 continued

NOTE: All values are in t/mth, unless otherwise stated.

	08/96	09/96	10/96	11/96	12/96
INPUTS					
Raw materials					
Impala matte	1453	1020	1224	1534	1418
Other toll ref.	187	446	463	297	260
Ni sulphate	1382	1570	1215	978	912
Co nitrate	128	154	79.9	139	39.8
Liquid reagents					
H_2SO_4 (kg)	1031427	1068203	1220766	1048185	1280710
HNO_3 (kg)	50720	50820	68280	63880	63500
Ammonia (kg)	908200	975410	950800	1136215	1033990
Gaseous reagents					
Oxygen (kg)	1172752	1043570	1360773	1197068	1514718
N_2	335	320	285	265	354
Inter-unit flows					
Steam	36821	34289	33210	37076	38170
Hydrogen used	75.4	74.3	53.3	78.7	86.7
CO_2 used	154	164	135	177	201
Standard flows					
Water	15094	17887	18954	17473	10164
TOTAL INPUTS	58793	59062	59221	61463	55498
OUTPUTS					
Main product					
Gross Ni produced	**1081.0**	**1113.0**	**1149.0**	**1237.0**	**1127.0**
Sintered Ni (A)	390.0	680.0	230.0	230.0	350.0
By-products					
Cu cathode	519	350	378	482	395
Co powder	7.30	10.30	6.50	7.00	7.00
Ammonium sulphate	2692	2939	2903	2764	2981
Se/Te solids	2.88	2.88	2.88	2.88	2.88
PGM concentrate	3.31	2.95	2.05	3.84	2.72
PGM solution	26.3	36.7	11.0	26.0	28.3
Wastes					
Jarosite	37.6	48.4	56.5	69.7	50.0
Effluent	7000	16604	13948	17806	10907
Standard flows					
Steam vented	18720	16400	15901	19507	20968
Cooling water losses	12929	12968	13010	10405	8260
N2 vented	335	320	285	265	354
Other open loop flows					
Demin to PMR	1149	1248	1561	1530	1021
Water to sewer	8392	8790	9114	9246	8996
TOTAL OUTPUTS	52895	60833	58328	63352	55100
INPUTS-OUTPUTS	5898	-1771	893	-1889	398
% ERROR	10.0	-3.0	1.5	-3.1	0.7
ENERGY INPUT					
Electricity (kWh)	6297020	6082597	5979635	6616577	6398399

A1 (iii): AVERAGE BMR PROCESS DATA: 1995

NOTE: All values are in t/mth, unless otherwise stated.
Average liquid reagent and oxygen values used from 01/95 to 07/95, inclusive.
Average electricity values used from 01/95 to 05/95, inclusive.

	01/95	02/95	03/95	04/95	05/95	06/95	07/95
INPUTS							
Raw materials							
Impala matte	1648	890	1838	1501	1343	1508	1289
Other toll ref.	78	100	153	43	168	224	160
Ni sulphate	575	929	756	800	1497	913	770
Co nitrate	74.5	133	229	188	169	102	100
Liquid reagents							
H_2SO_4 (kg)	1121086	1121086	1121086	1121086	1121086	1121086	1121086
HNO_3 (kg)	79280	60838	60838	60838	60838	60838	60838
Ammonia (kg)	943182	943182	943182	943182	943182	943182	943182
Gaseous reagents							
Oxygen (kg)	1176411	1176411	1176411	1176411	1176411	1176411	1176411
N_2	670	344	596	474	568	498	587
Inter-unit flows							
Steam	30000	26603	30105	32929	33716	36932	32424
Hydrogen used	72.3	55.0	76.0	81.1	82.3	84.9	74.2
CO_2 used	156	123	163	173	175	180	160
Standard flows							
Water	32360	29123	25652	33742	27247	24863	20865
TOTAL INPUTS	68953	61602	62870	73233	68266	68606	59730
OUTPUTS							
Main product							
Gross Ni produced	**878.6**	**607.0**	**1026.6**	**981.5**	**952.5**	**962.0**	**886.5**
Sintered Ni (A)	770.0	400.0	710.0	Unavailable	Unavailable	Unavailable	652.5
By-products							
Cu cathode	456	256	495	424	416	532	483
Co powder	5.60	5.20	7.00	9.17	6.40	8.00	6.00
Ammonium sulphate	2358	2567	2888	1956	2343	2582	2214
Se/Te solids	2.88	2.88	2.88	2.88	2.88	2.88	2.88
PGM concentrate	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PGM solution	72.1	42.6	37.5	52.9	27.3	42.8	52.3
Wastes							
Jarosite	56.6	40.2	100.4	42.3	68.9	54.1	38.8
Effluent	6820	14918	11317	23524	23123	22556	21621
Standard flows							
Steam vented	13593	10134	13711	16553	17345	20570	16024
Cooling water losses	9261	10127	10173	10129	10515	10922	9391
N2 vented	670	344	596	474	568	498	587
Other open loop flows							
Demin to PMR	910	910	910	910	495	393	761
Water to sewer	7548	7548	7548	2009	11434	9404	8651
TOTAL OUTPUTS	42632	47501	48813	57068	67297	68526	60718
INPUTS-OUTPUTS	26321	14101	14057	16165	969	79	-988
% ERROR	38.2	22.9	22.4	22.1	1.4	0.1	-1.7
ENERGY INPUT							
Electricity (kWh)	6466442	6466442	6466442	6466442	6466442	7461931	6967863

A1 (iii): AVERAGE BMR PROCESS DATA: 1995 continued

NOTE: All values are in t/mth, unless otherwise stated.
Average liquid reagent and oxygen values used from 08/95 to12/95, inclusive.

	08/95	09/95	10/95	11/95	12/95
INPUTS					
Raw materials					
Impala matte	1285	331	415	1119	1606
Other toll ref.	143	293	256	165	40
Ni sulphate	1331	1373	1428	1049	1017
Co nitrate	175	176	161	158	141
Liquid reagents					
H_2SO_4 (kg)	1121086	1121086	1121086	1121086	1121086
HNO_3 (kg)	60838	60838	60838	60838	60838
Ammonia (kg)	943182	943182	943182	943182	943182
Gaseous reagents					
Oxygen (kg)	1176411	1176411	1176411	1176411	1176411
N_2	723	399	419	278	478
Inter-unit flows					
Steam	34703	32366	26179	29536	34272
Hydrogen used	79.2	51.2	41.6	49.4	64.1
CO_2 used	169	116	98	113	141
Standard flows					
Water	19699	21008	26825	23138	15570
TOTAL INPUTS	61609	59415	59124	58906	56630
OUTPUTS					
Main product					
Gross Ni produced	**885.4**	**692.2**	**533.6**	**740.3**	**992.0**
Sintered Ni (A)	688.9	344.2	364.6	414.3	673.0
By-products					
Cu cathode	394	297	256	410	355
Co powder	7.60	6.60	3.40	8.00	7.40
Ammonium sulphate	2699	2640	1742	2353	2777
Se/Te solids	2.88	2.88	2.88	2.88	2.88
PGM concentrate	0.00	0.00	0.00	0.00	0.00
PGM solution	21.8	12.9	44.5	18.9	17.7
Wastes					
Jarosite	63.4	38.2	40.3	48.2	54.3
Effluent	26046	19320	15903	4816	3467
Standard flows					
Steam vented	18321	15957	7993	13398	18369
Cooling water losses	9493	9780	9977	10837	12444
N2 vented	723	399	419	278	478
Other open loop flows					
Demin to PMR	882	1394	2533	1467	462
Water to sewer	8306	9048	11137	6807	4885
TOTAL OUTPUTS	67845	59588	50585	41184	44310
INPUTS-OUTPUTS	-6236	-173	8539	17722	12319
% ERROR	-10.1	-0.3	14.4	30.1	21.8
ENERGY INPUT					
Electricity (kWh)	6897177	6200629	5709252	6403996	6609687

APPENDIX 2

MONTHLY BOILER AND HYDROGEN GENERATION DATA
AND WATER BALANCE
(PEMS INPUT DATA).

STEAM GENERATION CALCULATIONS.

100% combustion efficiency is assumed, thus residual sulphur and carbon in the ash is negligible.

The calculations are based on an average ultimate coal analysis of:

0.35% S
69.99% C
4.24% H
1.24% N
5.18% O
14.4% Ash
4.6% Moisture

Using the average case as an example, where 5411t/mth coal was used:
This relates to:

18939kg S
3787227kg C
229431kg H
67098kg N
280295kg O
779198kg Ash
248910kg Moisture

The relevant combustion reactions are:

$$S + O_2 \rightarrow SO_2$$
$$C + O_2 \rightarrow CO_2$$
$$4H + O_2 \rightarrow 2H_2O$$
$$N + O_2 \rightarrow NO_2$$

Thus SO_2 produced = 18939kg S * 64g/mol SO_2/32g/mol S
= <u>37878kg SO_2</u>

The oxygen required for this reaction = 18939 * 32g/mol O_2/32g/mol S
= <u>18939kg O_2</u>

Similarly, the CO_2 produced is 13886t, which requires 10099t O_2, while 2314t of water vapour would be produced (including the moisture in the coal) using 1835t O_2. 220t of NO_2 from N combustion would use 153t of O_2.

The overall oxygen requirement (from air) would thus be 11827t.

HYDROGEN GENERATION CALCULATIONS.

100% conversion efficiency is assumed.

The calculations are based on an average Sasol hydrogen rich gas analysis of:

36% CO
6% H_2
36% CH_4
13% CO_2

where the percentages are based on mass.

The remainder of the gas composition are inert components (N_2 and argon), which would not contribute to the environmental profile as determined using PEMS.

The relevant reactions are:

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$$
$$CO + H_2O \rightarrow CO_2 + H_2$$

As the quantity of gas used is measured in GJ and not as a mass, the amount of gas used was calculated from the measured hydrogen production. This avoided the use of an average calorific value for the hydrogen production reactions, which would have introduced an error because this value is known to fluctuate.

The average case is used as an example (all values are per month):

The hydrogen produced is derived from that which was in the feed gas, plus that which was produced from methane (and higher hydrocarbons, which are included as methane as an approximation because their relative composition varies) and carbon monoxide, according to the reactions given above.

Thus letting the mass of feed gas be = x, and using the average feed gas composition above:

$$0.06x + (0.36x * 2/28) + (0.36x * 8/16) = 81.5t\ H_2$$
$$\text{Thus } \underline{x = 306.7t}$$

The CO_2 produced could then be calculated from this mass of feed gas:

$$(0.13 * 306.7) + (0.36 * 44/28 * 306.7) + (0.36 * 44/16 * 306.7)$$
$$\text{Thus } CO_2 \text{ produced} = \underline{517t}$$

The steam required was included in the total steam usage by the hydrogen plant (which also included steam for heating).

The average calorific value of the gas was then calculated, as the feed gas consumption related to 10138GJ. An average calorific value of (10138/306.7) 33.1MJ/kg was thus calculated.

The heating calculations were then based on this value (as there were no measured values to base calculations on). 9807.3GJ of fuel gas was used, which equates to 297t.

The gas combustion reactions are:

$$CO + ½\ O_2 \rightarrow CO_2$$
$$H_2 + ½\ O_2 \rightarrow H_2O$$
$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

From these reactions (assuming 100% combustion) and the average gas composition, the CO_2 produced was calculated to be:

$$(0.36 * 297 * 44/28) + (0.36 * 297 * 44/16) + (0.13 * 297)$$
$$= \underline{500.7t\ CO_2}$$

Similarly, the water vapour produced was calculated to be 401t, and the oxygen requirement 631t. The N_2 in the gas of 27t would also enter the atmosphere (as given by the supplier as combustion products (Sasol, 1998)).

The overall error was thus estimated to be approximately 15%, based on changes in the gas composition, the error in the measurement of the hydrogen produced and the fuel gas GJ measurement, and the assumption of 100% conversion and combustion.

A2 (i): BOILER BALANCE: 1997

Quantities in kg, unless otherwise stated
Note: The effluent approximation was obviously too high for months which showed negative steam losses.

STREAM	SOURCE	07/97	06/97	05/97	04/97	03/97	02/97	01/97
Inputs								
Coal t	Mth end reports	6104	6817	6365	6066	5709	5187	5000
Coal kg		6104000	6817000	6365000	6066000	5709000	5187000	5000000
Oxygen (from air)	Calculated	13341164	14899527.36	13911616.79	13258110	12477835	11336930	10928214
Boiler feed water t	Logsheets	41792	45225	45362	45486	44208	42746	41513
Water for ash	34.5% moisture	462972	517051	482768	460090	433012	393420	379237
Outputs								
Ash t	Based on 14.4% ash	879	982	917	874	822	747	720
Ash kg		878976	981648	916560	873504	822096	746928	720000
Water in ash	34.5% moisture	462972	517051	482768	460090	433012	393420	379237
SO_2	Calculated	42728	47719	44555	42462	39963	36309	35000
CO_2	Calculated	15664695	17494467	16334500	15567176	14651007	13311398	12831500
H_2O	Calculated	2610070	2914949	2721674	2593822	2441168	2217961	2138000
NO_2	Calculated	248694	277744	259328	247146	232601	211333	203714
Effluent t	Estimated	750	750	750	750	750	750	750
Steam to PMR t	Logsheet or average	2012	2262	1987	1979	2225	2067	1724
Steam to H_2 t	Logsheet (05/97)	4589	4589	4589	4589	4589	4589	4589
Steam to BMR t	By difference (prod-H2-PMR)	34522	37350	37854	37851	36399	35042	34383
Thus steam loss at boilers	By difference	-81000	274000	182000	317000	245000	298000	67000
% Steam loss		-0.2	0.6	0.4	0.7	0.6	0.7	0.2
Electricity								
Boilers & general (kWh)	Elec data or average	761583	697001	674014	731672	590808	704120	784442
Boilers & general (MJ)	Elec data or average	2741700	2509205	2426450	2634020	2126910	2534833	2823993

Average coal analysis

% S	0.35
% C	69.99
% H	4.24
% N	1.24
% O	5.18
% Moisture	4.6

A2 (i): BOILER BALANCE: 1996

Quantities in kg, unless otherwise stated
Note: The effluent approximation was obviously too high for months which showed negative steam losses.

STREAM	SOURCE	12/96	11/96	10/96	09/96	08/96	07/96	06/96	05/96	04/96	03/96	02/96	01/96
Inputs													
Coal t	Mth end reports	5566	5447	4689	5055	5244	4586	4987	4792	5159	5766	5616	5060
Coal kg		5566000	5447000	4689000	5055000	5244000	4586000	4987000	4792000	5159000	5766000	5616000	5060000
Oxygen (from air)	Calculated	12165288	11905197	10248479	11048425	11461511	10023358	10899801	10473601	11275732	12602417	12274570	11059353
Boiler feed water t	Logsheets	45783	44624	40438	41752	44340	37597	37673	36836	35055	35399	38556	36914
Water for ash	34.5% moisture	422166	413140	355648	383408	397743	347836	378251	363460	391296	437336	425959	383787
Outputs													
Ash t	Based on 14.4% ash	802	784	675	728	755	660	718	690	743	830	809	729
Ash kg		801504	784368	675216	727920	755136	660384	718128	690048	742896	830304	808704	728640
Water in ash	34.5% moisture	422166	413140	355648	383408	397743	347836	378251	363460	391296	437336	425959	383787
SO_2	Calculated	38962	38129	32823	35385	36708	32102	34909	33544	36113	40362	39312	35420
CO_2	Calculated	14284026	13978636	12033381	12972647	13457677	11769052	12798138	12297710	13239542	14797286	14412341	12985478
H_2O	Calculated	2380022	2329137	2005016	2161518	2242334	1960974	2132441	2049059	2205988	2465542	2401402	2163656
NO_2	Calculated	226775	221926	191043	205955	213656	186847	203185	195240	210192	234923	228812	206159
Effluent t	Estimated	750	750	750	750	750	750	750	750	750	750	750	750
Steam to PMR t	Logsheet or average	2139	2182	2094	2235	2125	1868	1845	1937	1619	1727	2029	1639
Steam to H_2 t	Logsheet (05/97)	4589	4589	4589	4589	4589	4589	4589	4589	4589	4589	4589	4589
Steam to BMR t	By difference (prod-H2-PMR)	38170	37076	33210	34289	36821	30254	30202	29678	28094	28286	31166	29715
Thus steam loss at boilers	By difference	135000	27000	-205000	-111000	55000	136000	287000	-118000	3000	47000	22000	221000
% Steam loss		0.3	0.1	-0.5	-0.3	0.1	0.4	0.8	-0.3	0.0	0.1	0.1	0.6
Electricity													
Boilers & general (kWh)	Elec data or average	810530	807302	653558	720905	695080	734295	780940	728823	675494	626897	739471	727645
Boilers & general (MJ)	Elec data or average	2917909	2906288	2352807	2595257	2502288	2643462	2811383	2623763	2431777	2256830	2662094	2619523

Average coal analysis

% S	0.35
% C	69.99
% H	4.24
% N	1.24
% O	5.18
% Moisture	4.6

A2 (I): BOILER BALANCE: 1995

Quantities in kg, unless otherwise stated
Note: The effluent approximation was obviously too high for months which showed negative steam losses.

STREAM	SOURCE	12/95	11/95	10/95	09/95	08/95	07/95	06/95	05/95	04/95	03/95	02/95	01/95	AVERAGE
Inputs														
Coal t	Mth end reports	5872	5153	4660	5714	6030	5504	6117	5621	5582	4896	4443	4937	5411
Coal kg		5872000	5153000	4660000	5714000	6030000	5504000	6117000	5621000	5582000	4896000	4443000	4937000	5411097
Oxygen (from air)	Calculated	12834095	11262618	10185096	12488763	13179426	12029778	13369577	12285499	12200258	10700907	9710811.2	10790519	11826725
Boiler feed water t	Logsheets	41502	36769	33033	40166	42244	39788	44318	40856	39857	37124	33649	37114	40249
Water for ash	34.5% moisture	445376	390841	353449	433392	457359	417464	463958	426338	423380	371349	336990	374458	410417
Outputs														
Ash t	Based on 14.4% ash	846	742	671	823	868	793	881	809	804	705	640	711	779
Ash kg		845568	742032	671040	822816	868320	792576	880848	809424	803808	705024	639792	710928	779198
Water in ash	34.5% moisture	445376	390841	353449	433392	457359	417464	463958	426338	423380	371349	336990	374458	410417
SO_2	Calculated	41104	36071	32620	39998	42210	38528	42819	39347	39074	34272	31101	34559	37878
CO_2	Calculated	15069314	13224144	11958958	14663838	15474789	14124915	15698057	14425172	14325087	12564605	11402071	12669823	13886498
H_2O	Calculated	2510867	2203423	1992616	2443306	2578428	2353510	2615629	2403540	2386863	2093530	1899827	2111061	2313785
NO_2	Calculated	239242	209948	189862	232805	245679	224249	249224	229016	227427	199477	181021	201147	220464
Effluent t	Estimated	750	750	750	750	750	750	750	750	750	750	750	750	750
Steam to PMR t	Logsheet or average	1743	1409	1389	1790	1711	1873	1793	1749	1895	1895	1895	1895	1895
Steam to H_2 t	Logsheet (05/97)	4589	4589	4589	4589	4589	4589	4589	4589	4589	4589	4589	4589	4589
Steam to BMR t	By difference (prod-H2-PMR)	34272	29536	26179	32366	34703	32424	36932	33716	32929	30105	26603	30000	32907
Thus steam loss at boilers	By difference	148000	485000	126000	671000	491000	152000	254000	52000	-306000	-215000	-188000	-120000	108097
% Steam loss		0.4	1.4	0.4	1.7	1.2	0.4	0.6	0.1	-0.8	-0.6	-0.6	-0.3	0.3
Electricity														
Boilers & general (kWh)	Elec data or average	788508	720294	910884	873854	799958	1070365	992726	761583	761583	761583	761583	761583	761583
Boilers & general (MJ)	Elec data or average	2838629	2593059	3279182	3145874	2879847	3853313	3573815	2741700	2741700	2741700	2741700	2741700	2741700

Average coal analysis

% S	0.35
% C	69.99
% H	4.24
% N	1.24
% O	5.18
% Moisture	4.6

A2 (ii): HYDROGEN PLANT BALANCE: 1997

In kg, unless otherwise stated

STREAM	SOURCE	07/97	06/97	05/97	04/97	03/97	02/97	01/97
A: H_2 PRODUCTION								
Inputs								
Natural gas (feed) GJ	Mth end report	11607	12021	11355	11921	7461	9264	9081
Natural gas (feed) kg		395914	390269	386506	365054	343602	321398	295807
Steam (incl heating)	Logsheet (5/97)	4589000	4589000	4589000	4589000	4589000	4589000	4589000
Calorific value	Calc	29.3	30.8	29.4	32.7	21.7	28.8	30.7
Outputs								
Steam loss (kg)	By difference	4212316	4217687	4221268	4241677	4262087	4283213	4307561
H_2 PMR (kg)	Estimated	800	800	800	800	800	800	800
H_2 total (t)	Mth end report	105.2	103.7	102.7	97	91.3	85.4	78.6
H_2 total (kg)		105200	103700	102700	97000	91300	85400	78600
H_2 vented (t)	Performance rep. or avg	4.92	10.61	10.15	7.22	8.87	4.18	9.79
H_2 vented (kg)		4920	10610	10150	7220	8870	4180	9790
H_2 BMR (kg)	By difference	99480	92290	91750	88980	81630	80420	68010
CO_2 BMR (t)	Calc (1)	200	197	195	185	174	163	150
CO_2 BMR (kg)		200219	197365	195461	184613	173765	162536	149594
CO_2 vented (t)	Calc (2)	467	461	456	431	405	379	349
CO_2 vented (kg)		467179	460517	456076	430764	405451	379250	349052
Total CO2 (kg)	Calc	667398	657882	651538	615377	579215	541785	498645
Inputs-outputs		0	0	0	0	0	0	0
B: Heating (nat gas)								
Inputs								
Natural gas (fuel) GJ	Mth end reports	8879	10871	12394	14230	12086	10239	8570
Natural gas (fuel) kg	Calorific value as above	302862	352934	421871	435762	556598	355224	279161
Oxygen (air) (kg)	Calc	643798	750236	896778	926305	1183168	755104	593417
Outputs								
CO_2 (kg)	Calc	510539	594945	711155	734570	938265	598806	470586
H_2O vapour (kg)	Calc	408864	476460	569526	588278	751407	479552	376868
N_2 (kg)	Calc	27258	31764	37968	39219	50094	31970	25125
Inputs-outputs		0	0	0	0	0	0	0
Overall balance (in-out)		0	0	0	0	0	0	0

NOTE:

1 Assume 30% of CO_2 is used

2 Assume 70% of CO_2 is vented

Electricity H2 plant	(kWh/mth)	175943	170347	274706	307720	275940	224980	112918
Electricity H2 plant	(MJ/mth)	633396	613248	988942	1107791	993383	809927	406503
		Average						

A2 (ii): HYDROGEN PLANT BALANCE: 1996

In kg, unless otherwise stated

STREAM	SOURCE	12/96	11/96	10/96	09/96	08/96	07/96	06/96	05/96	04/96	03/96	02/96	01/96
A: H_2 PRODUCTION													
Inputs													
Natural gas (feed) GJ	Mth end report	10187	10179	6172	11094	9466	9432	9324	10840	8500	10522	11319	10027
Natural gas (feed) kg		397796	350376	266828	324032	304839	235215	276237	276613	222796	298441	308979	253656
Steam (incl heating)	Logsheet (5/97)	4589000	4589000	4589000	4589000	4589000	4589000	4589000	4589000	4589000	4589000	4589000	4589000
Calorific value	Calc	25.6	29.1	23.1	34.2	31.1	40.1	33.8	39.2	38.2	35.3	36.6	39.5
Outputs													
Steam loss (kg)	By difference	4210526	4255642	4335132	4280706	4298968	4365210	4326181	4325823	4377026	4305055	4295029	4347664
H_2 PMR (kg)	Estimated	800	800	800	800	800	800	800	800	800	800	800	800
H_2 total (t)	Mth end report	105.7	93.1	70.9	86.1	81	62.5	73.4	73.5	59.2	79.3	82.1	67.4
H_2 total (kg)		105700	93100	70900	86100	81000	62500	73400	73500	59200	79300	82100	67400
H_2 vented (t)	Performance rep. or avg	18.19	13.58	16.76	11.05	4.77	3.46	7.27	5.72	12.01	4.49	9.00	9.00
H_2 vented (kg)		18190	13580	16760	11050	4770	3460	7270	5720	12010	4490	9002	9002
H_2 BMR (kg)	By difference	86710	78720	53340	74250	75430	58240	65330	66980	46390	74010	72298	57598
CO_2 BMR (t)	Calc (1)	201	177	135	164	154	119	140	140	113	151	156	128
CO_2 BMR (kg)		201171	177190	134939	163868	154161	118952	139697	139887	112671	150926	156255	128277
CO_2 vented (t)	Calc (2)	469	413	315	382	360	278	326	326	263	352	365	299
CO_2 vented (kg)		469399	413444	314857	382358	359710	277554	325959	326403	262899	352160	364595	299314
Total CO2 (kg)	Calc	670570	590635	449796	546226	513871	396505	465656	466290	375570	503086	520850	427592
Inputs-outputs		0	0	0	0	0	0	0	0	0	0	0	0
B: Heating (nat gas)													
Inputs													
Natural gas (fuel) GJ	Mth end reports	10590	9380	12666	10370	9725	9166	10357	10557	8593	8917	9505	8977
Natural gas (fuel) kg	Calorific value as above	413533	322874	547577	302886	313180	228582	306841	269391	225233	252918	259461	227094
Oxygen (air) (kg)	Calc	879052	686337	1163992	643849	665730	485899	652256	572649	478782	537630	551540	482737
Outputs													
CO_2 (kg)	Calc	697098	544273	923058	510579	527931	385323	517246	454117	379679	426347	437377	382815
H_2O vapour (kg)	Calc	558269	435879	739229	408896	422792	308585	414235	363678	304065	341439	350273	306577
N_2 (kg)	Calc	37218	29059	49282	27260	28186	20572	27616	24245	20271	22763	23352	20438
Inputs-outputs		0	0	0	0	0	0	0	0	0	0	0	0
Overall balance (in-out)		0	0	0	0	0	0	0	0	0	0	0	0

NOTE:

1 Assume 30% of CO_2 is used

2 Assume 70% of CO_2 is vented

Electricity H2 plant	(kWh/mth)	156502	144898	171154	185611	190256	174789	197181	176529	161075	158815	186258	161843
Electricity H2 plant	(MJ/mth)	563406	521632	616156	668201	684922	629240	709853	635504	579868	571734	670527	582633

A2 (ii): HYDROGEN PLANT BALANCE: 1995

In kg, unless otherwise stated

STREAM	SOURCE	12/95	11/95	10/95	09/95	08/95	07/95	06/95	05/95	04/95	03/95	02/95	01/95	AVERAGE
A: H_2 PRODUCTION														
Inputs														
Natural gas (feed) GJ	Mth end report	12079	9690	7678	7672	10100	9861	11334	11691	11604	10964	10485	11333	**10138**
Natural gas (feed) kg		278118	222796	193441	229570	334946	316129	356398	346613	342097	322903	243871	308979	**306781**
Steam (incl heating)	Logsheet (5/97)	4589000	4589000	4589000	4589000	4589000	4589000	4589000	4589000	4589000	4589000	4589000	4589000	**4589000**
Calorific value	Calc	43.4	43.5	39.7	33.4	30.2	31.2	31.8	33.7	33.9	34.0	43.0	36.7	**33.0**
Outputs														
Steam loss (kg)	By difference	4324390	4377026	4404955	4370581	4270323	4288226	4249913	4259223	4263519	4281781	4356974	4295029	**4297120**
H_2 PMR (kg)	Estimated	800	800	800	800	800	800	800	800	800	800	800	800	**800**
H_2 total (t)	Mth end report	73.9	59.2	51.4	61	89	84	94.7	92.1	90.9	85.8	64.8	82.1	**81.5**
H_2 total (kg)		73900	59200	51400	61000	89000	84000	94700	92100	90900	85800	64800	82100	**81516**
H_2 vented (t)	Performance rep. or avg	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	**9.00**
H_2 vented (kg)		9002	9002	9002	9002	9002	9002	9002	9002	9002	9002	9002	9002	**9002**
H_2 BMR (kg)	By difference	64098	49398	41598	51198	79198	74198	84898	82298	81098	75998	54998	72298	**71714**
CO_2 BMR (t)	Calc (1)	141	113	98	116	169	160	180	175	173	163	123	156	**155**
CO_2 BMR (kg)		140648	112671	97826	116097	169387	159871	180236	175287	173003	163297	123329	156255	**155144**
CO_2 vented (t)	Calc (2)	328	263	228	271	395	373	421	409	404	381	288	365	**362**
CO_2 vented (kg)		328180	262899	228260	270893	395237	373032	420550	409003	403674	381026	287768	364595	**362002**
Total CO2 (kg)	Calc	468828	375570	326086	386989	564624	532903	600785	584290	576678	544323	411097	520850	**517145**
Inputs-outputs		0	0	0	0	0	0	0	0	0	0	0	0	
B: Heating (nat gas)														
Inputs														
Natural gas (fuel) GJ	Mth end reports	7091	9162	7033	7163	9984	9410	9483	9904.8	10055.1	9728.6	9443.9	9496.6	**9807.3**
Natural gas (fuel) kg	Calorific value as above	163270	210656	177191	214339	331099	301671	298193	293656	296434	286519	219656	258912	**296789**
Oxygen (air) (kg)	Calc	347065	447794	376657	455624	703823	641266	633874	624229	630134	609058	466926	550372	**630888**
Outputs														
CO_2 (kg)	Calc	275226	355105	298693	361314	558139	508531	502669	495020	499703	482990	370277	436451	**500301**
H_2O vapour (kg)	Calc	220414	284385	239207	289358	446984	407255	402561	396436	400186	386801	296536	349531	**400665**
N_2 (kg)	Calc	14694	18959	15947	19291	29799	27150	26837	26429	26679	25787	19769	23302	**26711**
Inputs-outputs		0	0	0	0	0	0	0	0	0	0	0	0	
Overall balance (in-out)		0	0	0	0	0	0	0	0	0	0	0	0	

NOTE:

1 Assume 30% of CO_2 is used

2 Assume 70% of CO_2 is vented

Electricity H2 plant	(kWh/mth)	189924	255978	175943	108070	86446	92531	58174	175943	175943	175943	175943	175943	**175943**
Electricity H2 plant	(MJ/mth)	683726	921520	633396	389053	311207	333113	209425	633396	633396	633396	633396	633396	**633396**
				Average					Average	Average	Average	Average	Average	

A2 (iii): WATER BALANCES: 1997

Quantities in t, unless otherwise indicated.

STREAM	SOURCE	07/97	06/97	05/97	04/97	03/97	02/97	01/97
Inputs								
BMR RWB	Logsheet	60525	59871	62161	61669	61975	59836	57008
Outputs								
CW make-up[1]	Logsheet	13640	12720	13012	13939	12805	13630	13336
Demin to PMR	Logsheet or avg	1124	757	767	579	672	901	692
Steam to PMR	Logsheet or avg	2012	2262	1987	1979	2225	2067	1724
Sewer[2]	General cons. ex logsheet or avg	6211	6554	4866	6523	7018	7151	7713
Water in ash	34.5% moisture	463	517	483	460	433	393	379
Moisture in jarosite	Avg, using 25% moisture	15	15	15	15	15	15	15
Effluent[3]	See calculation below	12854	23123	9801	12287	14213	2441	23994
Vented steam[4]	See calculation below	22398	23238	29219	25957	24344	22728	22562
Total outputs		58717	69186	60150	61739	61725	49326	70415
					CW2+10%CW2			
IN-OUT		**1808**	**-9315**	**2011**	**-70**	**250**	**10510**	**-13407**
% ERROR (in-out/in)		**3**	**-16**	**3**	**0**	**0**	**18**	**-24**

Effluent calc:

Effluent to Ergo	Month end report	17612	35812	30956	29817	21255	28273	26755
Evaporation	Month end balance or avg	462	589	63	820	1073	1482	1239
Pond level change	Month end balance or avg	-5220	3960	-19960	0	16000	-9000	11160
Rain	Month end balance or avg	0	17238	1258	18350	24115	18314	15160
Thus effluent into pond		12854	23123	9801	12287	14213	2441	23994

Vented steam calc:

Steam prod	Month end report	41123	44201	44430	44419	43213	41698	40696
Condensate returns	Logsheet or avg	8736	11347	7143	9075	9075	9075	9075
Seal water returns	Logsheet or avg	7896	7628	6263	7725	7814	8126	7402
Steam to PMR	Logsheet or avg	2012	2262	1987	1979	2225	2067	1724
Steam loss at boilers	Calculated	-81	274	182	317	245	298	67
Thus steam loss		22398	23238	29219	25957	24344	22728	22562

BMR water balance:

Inputs								
RWB water	Total RWB-boiler feed-ash water	18270	14129	16316	15723	17334	16697	15116
Steam to BMR	As above	34522	37350	37854	37851	36399	35042	34383
Total inputs		52792	51479	54170	53574	53733	51739	49499
Outputs								
CW losses	Logsheet	13640	12720	13012	13939	12805	13630	13336
Effluent	As above, less boiler effluent	12104	22373	9051	11537	13463	1691	23244
Demin to PMR	Logsheet or average	1124	757	767	579	672	901	692
Sewer	As above	6211	6554	4866	6523	7018	7151	7713
Jarosite	As above	15	15	15	15	15	15	15
Steam vented	Total loss-boilers-H_2	18267	18746	24816	21398	19837	18147	18187
% steam vented		53	50	66	57	54	52	53
Total outputs		51361	61165	52527	53991	53810	41535	63187
% error		3	-19	3	-1	0	20	-28
H_2 plant steam loss in kg	H_2 plant balance	4212316	4217687	4221268	4241677	4262087	4283213	4307561

NOTES:

1 Assume all CW required for make-up is due to evaporative losses. Where data on CW1 was not available, 10% of CW2 make-up was used.

2 Assume all RWB in for general use leaves the plant via the sewer, except for 20kl/day which is used for washing by Utilities, and would thus enter the effluent pond via the stormwater drains. The remainder is used for toilets, showers, drinking water etc.

3 Effluent is calculated by adding the effluent pumped to Ergo, the evaporative losses from the pond, the change in the pond level, and subtracting the rain.

4 Assume the difference between BFW and steam produced is due to boil downs & steam losses at the boilers. Condensate returns via tank 2906, and seal water are deducted from the BFW, to give the overall steam loss. (The demin make-up to seal water is subtracted from the total makeup) Steam generated from process liquors is, for the most part, condensed and recycled, and contaminated process water is returned to 2nd stage leach.

The average obtained above compares favorably with estimated vapour losses, as previously calculated (in 1992), where a value of 25500t/mth was arrived at. A somewhat lower value would be expected now, as some of the processes are no longer in operation.

A2 (III): WATER BALANCES: 1996

Quantities in t, unless otherwise indicated.

STREAM	SOURCE	12/96	11/96	10/96	09/96	08/96	07/96	06/96	05/96	04/96	03/96	02/96	01/96
Inputs													
BMR RWB	Logsheet	56389	62510	59748	60022	59832	52397	56632	58357	55725	55040	63303	58169
Outputs													
CW make-up[1]	Logsheet	8260	10405	13010	12968	12929	8863	9933	11977	11111	10050	12515	10300
Demin to PMR	Logsheet or avg	1021	1530	1561	1248	1149	732	573	762	592	444	662	425
Steam to PMR	Logsheet or avg	2139	2182	2094	2235	2125	1868	1845	1937	1619	1727	2029	1639
Sewer[2]	General cons. ex logsheet or avg	8996	9246	9114	8790	8392	6272	5525	6101	6835	8532	8338	7499
Water in ash	34.5% moisture	422	413	356	383	398	348	378	363	391	437	426	384
Moisture in jarosite	Avg, using 25% moisture	15	15	15	15	15	15	15	15	15	15	15	15
Effluent[3]	See calculation below	11657	18556	14698	17354	7750	11554	15148	9282	6919	5682	-3363	1059
Vented steam[4]	See calculation below	25314	23790	20031	20570	23074	17704	16957	16638	18132	18564	18510	18413
Total outputs		57824	66137	60879	63563	55832	47356	50374	47075	45614	45451	39132	39734

IN-OUT		**-1456**	**-3627**	**-1131**	**-3541**	**4000**	**6041**	**6268**	**11282**	**10111**	**9589**	**24171**	**18436**
% ERROR (in-out/in)		**-3**	**-6**	**-2**	**-6**	**7**	**10**	**11**	**19**	**18**	**17**	**38**	**32**

Effluent calc:

Effluent to Ergo	Month end report	45700	25550	23189	23849	10352	24162	21054	6812	20063	26005	31610	28228
Evaporation	Month end balance or avg	1352	1711	1482	713	636	912	453	586	612	905	604	1655
Pond level change	Month end balance or avg	-13680	17020	-7500	-5920	-1980	-331	-6300	5250	350	-4400	11760	4320
Rain	Month end balance or avg	21715	25725	2473	1288	1258	13189	59	3366	14106	16828	47337	33144
Thus effluent into pond		11657	18556	14698	17354	7750	11554	15148	9282	6919	5682	-3363	1059
							Avgs used						

Vented steam calc:

Steam prod	Month end report	44898	43847	39893	41113	43535	36711	36636	36204	34302	34602	37784	35943
Condensate returns	Logsheet or avg	9075	9075	9075	9075	9075	9075	9075	9075	9075	9075	9075	9075
Seal water returns	Logsheet or avg	8505	8627	8488	9122	9316	8200	9046	8436	5479	5283	8192	7037
Steam to PMR	Logsheet or avg	2139	2182	2094	2235	2125	1868	1845	1937	1619	1727	2029	1639
Steam loss at boilers	Calculated	135	27	-205	-111	55	136	287	-118	3	47	22	221
Thus steam loss		25314	23790	20031	20570	23074	17704	16957	16638	18132	18564	18510	18413

BMR water balance:

Inputs													
RWB water	Total RWB-boiler feed-ash water	10164	17473	18954	17887	15094	14452	18581	21158	20279	19204	24321	20871
Steam to BMR	As above	38170	37076	33210	34289	36821	30254	30202	29678	28094	28286	31166	29715
Total inputs		48334	54549	52184	52176	51915	44706	48783	50836	48373	47490	55487	50586
Outputs													
CW losses	Logsheet	8260	10405	13010	12968	12929	8863	9933	11977	11111	10050	12515	10300
Effluent	As above, less boiler effluent	10907	17806	13948	16604	7000	10804	14398	8532	6169	4932	-4113	309
Demin to PMR	Logsheet or average	1021	1530	1561	1248	1149	732	573	762	592	444	662	425
Sewer	As above	8996	9246	9114	8790	8392	6272	5525	6101	6835	8532	8338	7499
Jarosite	As above	15	15	15	15	15	15	15	15	15	15	15	15
Steam vented	Total loss-boilers-H_2	20968	19507	15901	16400	18720	13203	12344	12430	13752	14212	14193	13844
% steam vented		55	53	48	48	51	44	41	42	49	50	46	47
Total outputs		50167	58509	53549	56025	48205	39889	42788	39817	38474	38185	31610	32392
% error		-4	-7	-3	-7	7	11	12	22	20	20	43	36
H_2 plant steam loss in kg	H_2 plant balance	4210526	4255642	4335132	4280706	4298968	4365210	4326181	4325823	4377026	4305055	4295029	4347664

A2 (III): WATER BALANCES: 1995

Quantities in t, unless otherwise indicated.

STREAM	SOURCE	12/95	11/95	10/95	09/95	08/95	07/95	06/95	05/95	04/95	03/95	02/95	01/95	AVERAGE
Inputs														
BMR RWB	Logsheet	57517	60298	60211	61607	62400	61070	69645	68529	74022	63147	63109	69848	**61060**
Outputs														
CW make-up[1]	Logsheet	12444	10837	9977	9780	9493	9391	10922	10515	10129	10173	10127	9261	**11240**
Demin to PMR	Logsheet or avg	462	1467	2533	1394	882	761	393	495	910	910	910	910	**910**
Steam to PMR	Logsheet or avg	1743	1409	1389	1790	1711	1873	1793	1749	1895	1895	1895	1895	**1895**
Sewer[2]	General cons. ex logsheet or avg	4885	6807	11137	9048	8306	8651	9404	11434	2009	7548	7548	7548	**7548**
Water in ash	34.5% moisture	445	391	353	433	457	417	464	426	423	371	337	374	**410**
Moisture in jarosite	Avg, using 25% moisture	15	15	15	15	15	15	15	15	15	15	15	15	**15**
Effluent[3]	See calculation below	4217	5566	16653	20070	26796	22371	23306	23873	24274	12067	15668	7570	**13466**
Vented steam[4]	See calculation below	22841	18260	12524	20999	23082	20464	25074	21656	20511	17778	14303	17768	**20703**
Total outputs		47052	44752	54581	63529	70742	63943	71371	70163	60166	50757	50803	45341	**66188**

PMR steam avg Avg gen use
Demin PMR avg

IN-OUT		**10465**	**15546**	**5630**	**-1922**	**-8342**	**-2873**	**-1726**	**-1634**	**13856**	**12390**	**12306**	**24507**	**4862**
% ERROR (in-out/in)		**18**	**26**	**9**	**-3**	**-13**	**-5**	**-2**	**-2**	**19**	**20**	**19**	**35**	**8**

Effluent calc:

Effluent to Ergo	Month end report	33023	32789	25143	25317	26575	17190	29929	37887	30709	26877	25605	20178	**26073**
Evaporation	Month end balance or avg	1707	1516	538	905	704	861	577	1030	675	1056	428	912	**912**
Pond level change	Month end balance or avg	-2520	-1800	7200	-3240	0	4320	-7200	-10800	18000	-5040	-4365	-331	**-331**
Rain	Month end balance or avg	27993	26939	16228	2912	483	0	0	4244	25110	10826	6000	13189	**13189**
Thus effluent into pond		4217	5566	16653	20070	26796	22371	23306	23873	24274	12067	15668	7570	**13466**

Avgs used

Vented steam calc:

Steam prod	Month end report	40604	35534	32157	38745	41003	38886	43314	40054	39413	36589	33087	36484	**39391**
Condensate returns	Logsheet or avg	9075	9075	9075	9075	9075	9075	9075	9075	9075	9075	9075	9075	**9075**
Seal water returns	Logsheet or avg	7093	7275	9295	7552	7626	7626	7626	7626	7626	7626	7626	7626	**7626**
Steam to PMR	Logsheet or avg	1743	1409	1389	1790	1711	1873	1793	1749	1895	1895	1895	1895	**1895**
Steam loss at boilers	Calculated	148	485	126	671	491	152	254	52	-306	-215	-188	-120	**108**
Thus steam loss		22841	18260	12524	20999	23082	20464	25074	21656	20511	17778	14303	17768	**20703**

BMR water balance:

Inputs														
RWB water	Total RWB-boiler feed-ash water	15570	23138	26825	21008	19699	20865	24863	27247	33742	25652	29123	32360	**20391**
Steam to BMR	As above	34272	29536	26179	32366	34703	32424	36932	33716	32929	30105	26603	30000	**32907**
Total inputs		49842	52674	53004	53374	54402	53289	61795	60963	66671	55757	55726	62360	**53298**
Outputs														
CW losses	Logsheet	12444	10837	9977	9780	9493	9391	10922	10515	10129	10173	10127	9261	**11240**
Effluent	As above, less boiler effluent	3467	4816	15903	19320	26046	21621	22556	23123	23524	11317	14918	6820	**12716**
Demin to PMR	Logsheet or average	462	1467	2533	1394	882	761	393	495	910	910	910	910	**910**
Sewer	As above	4885	6807	11137	9048	8306	8651	9404	11434	2009	7548	7548	7548	**7548**
Jarosite	As above	15	15	15	15	15	15	15	15	15	15	15	15	**15**
Steam vented	Total loss-boilers-H_2	18369	13398	7993	15957	18321	16024	20570	17345	16553	13711	10134	13593	**16298**
% steam vented		54	45	31	49	53	49	56	51	50	46	38	45	**50**
Total outputs		39642	37340	47558	55514	63063	56463	63860	62927	53140	43674	43652	38147	**48728**
% error		20	29	10	-4	-16	-6	-3	-3	20	22	22	39	**9**
H_2 plant steam loss in kg	H_2 plant balance	4324390	4377026	4404955	4370581	4270323	4288226	4249913	4259223	4263519	4281781	4358974	4295029	**4297120**

Avg seal water used

APPENDIX 3

OVERALL AVERAGE
ELEMENTAL MASS BALANCE DATA.

A3 (i): MONTHLY ANALYTICAL DATA: UNITS

* Actual monthly values, or Metsim values Values in brackets were not routinely available

	IMPALA MATTE	WMC MATTE	WESTAIM NISO4	NORTHAM NISO4	WESTERN NISO4	UHPU Co nitrate	SOLIDS EX 1st	FILT EX Cu CEM TO JARO	JAROSITE RES	FILT EX JARO TO Ni PUR	HNO3 E/S EX NI TO Cu CEM	Fe RES EX NI TO JARO	NI PRODUCT	Cu EX SAT RED SOL EX NI TO MDS	SOLN EX MDS TO Ni PUR	SOLN EX MDS TO AMM SUL	MDS CAKE TO Co	RTZ Co CAKE TO Co	NI RECY EX Co TO NI	Fe SLURRY EX Co TO JARO	Co E/S TO MDS	Co PRODUCT
Source	Analyses	Analyses	Analyses	Analyses	Analyses	Analyses	1121&2121	SAT 2170	2176	SAT 2177	N/ANALY	N/ANALY	Calc	PERF 580	PERF 6016	PERF 6016	SAT 6100		SAT 6210	N/A 6700	N/ANALY	MTH END
Flowrates*	t/mth	t/mth	t/mth	t/mth	t/mth	kl/mth	kg/h	lpm	kg/h	lpm	lpm	kg/h	kg/h	lpm	lpm	lpm	kg/h	t/mth	lpm	lpm	lpm	kg/h
Metsim adj factor	Based on 777t/mth Ni input in total matte (Impala + WMC)																					
Adjusted Metsim flows	t/mth	t/mth	t/mth	t/mth	t/mth	kl/mth	kg/h	lpm	kg/h	lpm	lpm	kg/h	kg/h	lpm	lpm	lpm	kg/h	t/mth	lpm	lpm	lpm	kg/h
Ni	%	%	%	%	%		%	g/l	%	g/l	g/l	g/l	%	g/l	g/l	g/l	g/l	%	g/l	ppm	ppm	ppm
Cu	%	%	%	%	%		%	g/l	%	g/l	ppm	ppm	%	g/l				%	g/l	ppm	ppm	ppm
Co	%	%	%	%	%	g/l	%	g/l	%		ppm	g/l	%	g/l	g/l	g/l	g/l	%	g/l	g/l	ppm	%
Fe	%		(%)				%	g/l	%	g/l	ppm	g/l	%				ppm	%	g/l	ppm	ppm	ppm
S	%								%				%									%
Pt	ppm	ppm					%		ppm													
Total PGMS							g/t															
Si							%						%									
Se	ppm	ppm	(ppm)								ppm	ppm	%							ppm	ppm	ppm
Te	ppm	ppm	(ppm)								ppm	ppm	%							ppm	ppm	
Pb	ppm	ppm	(ppm)					ppm	%	ppm	ppm	ppm	%							ppm	ppm	ppm
Pd	ppm	ppm							ppm													
Au	ppm	ppm							ppm													
Rh	ppm	ppm							ppm													
Ru	ppm	ppm							ppm													
Ir	ppm	ppm							ppm													
Ag	ppm	ppm							ppm													
As	ppm		(%)						%		ppm	ppm	%							ppm	ppm	ppm
Free H_2SO_4			(%)																			
H_2O									%													
Na															g/l	g/l						
N																						%
C													%									%
Zn													%									ppm
Sn													%									
Bi													%									
Sb													%									
P													%									
Mn													%						g/l			ppm
Cd																						ppm
O																						%
$(NH_4)_2SO_4$														g/l	g/l	g/l			g/l			
Free NH_3																	g/l		g/l			
Cl															ppm	ppm						

Flowrates*	Mth end NaHS MTH END t/mth	Mth end SO_2 MTH END t/mth	Mth end H_2SO_4 leaches MTH END t/mth	Mth end H_2SO_4 nickel MTH END t/mth	Mth end OXYGEN t/mth	Mth end AMMONIA t/mth	Mth end HYDROGEN t/mth	Mth end WATER t/mth	Perf report AIR m^3/mth	Perf report STEAM t/mth	Logsheet HNO_3 t/mth	Process FERROUS SULPHATE t/mth	Logsheet SODIUM FORMATE t/mth	Logsheet NaOH t/mth	Logsheet H_2SO_4 utilities t/mth

A3 (i): MONTHLY ANALYTICAL DATA: UNITS (cont.)

Values in brackets were not routinely available
* Actual monthly values, or Metsim values

	AMM SULPH	Co PURGE EX AMM TO MDS	SOLIDS EX 2nd	SOLN EX 2nd TO Cu PUR	SOLIDS EX 3rd	FILT EX 3rd TO Cu CEM	RTZ RESIDUE TO 2nd	SOLIDS EX 4th	FILT EX 4th TO 1st	Se/Te EX 4th	SOLIDS EX 5th	SOLN EX 5th	Se/Te EX Cu PUR	FEED TO Cu WIN	ELECT EX Cu WIN	Cu PRODUCT	Mth end EFFLUENT
Source	3122	PERF 3102	2221	SAT 2221	3318	SAT 3830		3418	SAT 3870	3874	3570	4770	2510	303	313	MTH END	935D
Flowrates*	kg/h	lpm	kg/h	lpm	kg/h	lpm	t/mth	kg/h	lpm	kg/h	kg/h	lpm	kg/h	lpm	lpm	kg/h	kl/mth
Metsim adj factor																	
Adjusted Metsim flows	kg/h	lpm	kg/h	lpm	kg/h	lpm	t/mth	kg/h	lpm	kg/h	kg/h	lpm	kg/h	lpm	lpm	kg/h	
Ni	%		%	g/l	%		%	%		%	%	ppm	%	g/l	g/l	ppm	g/l
Cu	%		%	g/l	%		%	%	g/l	%	%	ppm	%	g/l	g/l	%	g/l
Co	%	g/l	%				%							g/l	g/l		g/l
Fe			%	g/l	%			%	g/l	%	%	ppm	%	g/l	g/l	ppm	g/l
S	%									%	%		%			ppm	g/l
Pt			%		%		ppm	%		%	%	ppm	%			ppm	
Total PGMS			%		%			%		%	%		%				
Si			%		%			%		%	%	ppm	%				
Se			%	ppm	%		ppm	%	ppm	%	%	ppm	%	ppm	ppm	ppm	ppm
Te			%	ppm	%		ppm	%	ppm	%	%	ppm	%	ppm	ppm	ppm	ppm
Pb			%		%			%		%	%	ppm	%	ppm	ppm	ppm	
Pd			%		%		ppm	%		%	%	ppm	%			ppm	
Au			%		%		ppm	%		%	%	ppm	%			ppm	
Rh			%		%		ppm	%		%	%	ppm	%			ppm	
Ru			%		%		ppm	%		%	%	ppm	%			ppm	
Ir			%		%		ppm	%		%	%	ppm	%			ppm	
Ag			%				ppm				%	ppm				ppm	
As					%		ppm	%		%	%	ppm	%	ppm	ppm	ppm	
Free H_2SO_4				g/l		g/l			g/l					g/l	g/l		
H_2O																	
Na	%	g/l									%						
N	%																
C											%					ppm	
Zn																	ppm
Sn																ppm	
Bi																ppm	
Sb																ppm	
P																	
Mn																	
Cd																	
O																ppm	
$(NH_4)_2SO_4$		g/l															
Free NH_3																	g/l
Cl		ppm															

A3 (II): AVERAGE CUMULATIVE DATA:-

ORIGINAL INFO.

PGM's are excluded for confidentiality reasons

	MATTE	MSO4	Co nitrate	SOLIDS EX 1st 1121	SOLIDS EX 1st 2121	FILT EX Cu CEM TO JARO	JAROSITE RES	FILT EX JARO TO Ni PUR	HNO3 E/S EX NI TO Cu CEM	Fe RES EX NI TO JARO	NI PRODUCT	RED SOL EX NI TO MDS	SOLN EX MDS TO NI PUR	SOLN EX MDS TO AMM SUL	MDS CAKE TO Co	RTZ Co CAKE	NI RECY EX Co TO NI	Fe SLURRY EX Co TO JARO	Co E/S TO MDS	Co PRODUCT
Flowrates	l/d & kg/d	l/d	105	1790		192	35	208	4.33	0.000243	1230	387	239	152	3.55	2.40	7.24	1.74	5.86	5
Metsim ADJ factor	0.94						42.3				966.8									7.2
ADjusted Metsim flows				1891		181	33	195	4	0.000230	1162	347	226	144	3		7	2	6	5
	S: Assume 12%(impals) & 20.49% (WMC)																			
Ni	24.495	6.089	1.01	18.6	11.51	103.8	3.45	99.7	55	91	1382.12	3.20	0.177	0.177	11.9	11.78	113.78	3219.5	1	280.58
Cu	13.411	0.003		51	58.52	0.003	0.05	0.002	4.4	23	0.08	0.001			0.00	0.585	0.00	1.2	1	28.39
Co	0.168	0.041	13.8	0.10	0.09	0.89	0.05	0.853	147	1409	1.36	0.84	0.2033	0.2033	12.8	41.09	1.93	3.7	1097	99.89
Fe	0.305	0.10	13.2	0.29	0.38	1.4	36.06	0.005	5.83	3825	0.10				5	1.52	0.00	1	1	18.10
S	10.12	12%	43.4	0.00	0.00		10.84				0.14									0.02
Si	0.00			0.07	0.10		0.00				0.01									0.00
Se	33.35						0.00		1	1	0.01							1	1	10.00
Te	11.08						0.00		1	1	0.01							1	1	0.00
Pb	6.90					1.5	0.14	0.03	1	1	0.00							1	1	2.58
As	17.85						1.13		1	1	0.00							1	1	1.33
Free H_2SO_4							0.00													0.00
H_2O							25.54													0.00
Na													2.44	2.44						0.00
N_2																				0.00
C											0.48									0.03
Zn																				
Sn																				
Bi																				
Sb																				
P																				
Mn																	7.54			2.84
Cd																				1.08
O																				0.13
$(NH_4)_2SO_4$												491	491	491			285.63			
Free NH_3															9.3		114.68			
Cl													58.2	58.2						

	NaHS t	SO_2 t	H_2SO_4 leaches t	H_2SO_4 nickel t	OXYGEN t	AMMONIA t	HYDROGEN t	WATER t	AIR m^3	STEAM t	HNO_3 t	FERROUS SULPHATE t	SODIUM FORMATE t	NaOH t	H_2SO_4 utilities t
Flowrates	5	27	681	401	1179	947	92	7636	2890	34812	60.8	1	12.39	1.18	19.8
Metsim ADJ factor															
ADjusted Metsim flows															
Ni															
Cu															
Co															
Fe												20.1			
S	57	50	33	33								11.5			33

CHANGE OF UNITS TO kg/h

	MATTE	MSO4	Co nitrate	SOLIDS EX 1st		FILT EX Cu CEM TO JARO	JAROSITE RES	FILT EX JARO TO NI PUR	HNO3 E/S EX NI TO Cu CEM	Fe RES EX NI TO JARO	NI PRODUCT	RED SOL EX NI TO MDS	SOLN EX MDS TO NI PUR	SOLN EX MDS TO AMM SUL	MDS CAKE TO Co	NI RECY EX Co TO NI	Fe SLURRY EX Co TO JARO	Co E/S TO MDS	RTZ Co CAKE	Co PRODUCT
ORIG UNITS	l/d&kg/d	l/d	l/d	%&g/l		g/l&ppm	%&ppm	g/l&ppm	g/l & ppm	g/l & ppm	kg/h	g/l	g/l	g/l	g/l & ppm	g/l	g/l & ppm	ppm	%&ppm	%&ppm
Ni	1020.83	253.76	0.15	228		1129	2.03	1184	13.5	0.0011	1382.12	66.5	2.4	1.5	2.4	48.7	0.3	0.00	0.39	0.003
Cu	558.79	0.13		851		0.03	0.03	0.023	0.001	0.0000	0.08	0.021				0.001	0.00	0.00	0.02	0.000
Co	6.90	1.71	2.01	1.55		9.7	0.03	9.963	0.030	0.00002	1.36	17.5	2.8	1.8	2.8	0.8	0.4	0.4	1.39	10.0
Fe	12.71	4.29	1.93	5.77		15.3	21.19	0.054	0.001	0.00005	0.10				0.00	0.001	0.00	0.00	0.05	0.000
S	421.77	188	8.33	0			8.25				0.14									0.001

FACTORS USED FOR THE APPORTIONING OF REAGENTS TO UNIT OPERATIONS

	NaHS MTH END	SO_2 MTH END	H_2SO_4 leaches MTH END	H_2SO_4 nickel MTH END	OXYGEN MTH END	AMMONIA MTH END	HYDROGEN MTH END	WATER MTH END	AIR PERFORM.	STEAM PERFORM.
Comminution								0.021237		
1st stage & Cu cem	1		0.1574904		0.2922268			0.031313	0.74911825	0.970380818
Jarosite					0.0021754	0.0539855		0.1094404		
Ni pur & redn						0.6668667	0.99251456	0.3317315	0.25898883	
MDS					0.7115903	0.1123188				
Co pur & redn					0.2884097	0.0029005	0.0800725	0.0074854	0.021518	0.01270183
Amm sulphate										
2nd stage			0.7881718		0.8707438			0.4309409		
3rd stage			0.0189501		0.0217539			0.0197489		0.009873061
4th stage		0.0788748	0.037388		0.0101518			0.0133623		0.009873061
5th stage					4.78E-05			0.0044954		0.009873061
Cu purification		0.9211252						0.0052705		
Cu winning						0.0869565		0.010944		

A3 (II): AVERAGE CUMULATIVE DATA: (cont.) -

ORIGINAL INFO.

PGM's are excluded for confidentiality reasons

	AMM SULPH	Co PURGE EX AMM TO MDS	SOLIDS EX 2nd	SOLN EX 2nd TO Cu PUR	RTZ RESIDUE TO 2ND	SOLIDS EX 3rd	FILT EX 3rd TO Cu CEM	SOLIDS EX 4th	FILT EX 4th TO 1st	Se/Te EX 4th	SOLIDS EX 5th	SOLN EX 5th	Se/Te EX Cu PUR	FEED TO Cu WIN	ELECT EX Cu WIN	Cu PRODUCT	EFFLUENT kl
Flowrates	3980	6.25	79	161	121	43.8	7.02	16.6	4.86	1	16.8	1.57	9	162	172	610	26073
Metsim AGj factor	2592															411.9	
AGjusted Metsim flows	3740	6	75	152		5	7	16	5	1	16	1	9	153	162	576	
Ni	0.02		6.93	36.8	4.609	2.63	0.00	1.16	0.00	0.39	1.32	35.14	3.72	37.08	35.42	101.19	0.212
Cu	0.00		16.97	100	19.939	26.07	0.00	2.65	26.70	30.01	2.68	683.20	41.81	74.81	23.08	99.87	0.027
Co	0.02	1.51	0.23	0.28	0.078	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.28	0.29	0.00	0.017
Fe	0.00		4.17	1.0	0.000	1.97	0.00	1.49	0.83	0.20	2.05	8.89	0.38	0.92	0.93	18.03	0.001
S	24.76		0.00		0.000	0.00	0.00	0.00	0.00	2.40	0.97	0.00	2.40	0.00	0.00	150.42	1.156
Si	0.00		0.81		0.000	1.88	0.00	3.57	0.00	0.39	4.70	534.49	0.63	0.00	0.00	0.00	0.000
Se	0.00		2.98	99	0.000	6.65	0.00	8.36	172.30	27.29	1.38	20402.06	8.95	0.78	5.34	61.94	2
Te	0.00		0.66	125	0.000	3.22	0.00	1.28	77.11	5.86	1.35	14.29	5.74	3.89	5.84	33.35	2
Pb	0.00		0.71		0.000	1.47	0.00	2.69	0.00	0.33	2.91	8.21	1.38	23.23	15.71	60.68	0
As	0.00					1.92	0.00	1.73	0.00	0.56	0.98	4374.23	0.56	234.45	237.58	0	0
Free H_2SO_4	0.00			24			57.15		75.00		0.00			25.19	101.19	0	0
H_2O	0.00										0.00					0	0
Na	0.23	38.28									2.38					0	0
N_2	20.61										0.00					0	0
C											1.90					50.064516	0
Zn																0	0.8
Sn																0	0.0
Bi																3.0322581	0.0
Sb																0	0.0
P																0	0.0
Mn																0	0.0
Cd																0	0.0
O																654.83871	0.0
$(NH_4)_2SO_4$		631.58															0.0
Free NH_3																	5.26
Cl		891.01															

CHANGE OF UNITS TO kg/h

	AMM SULPH	Co PURGE EX AMM TO MDS	SOLIDS EX 2nd	SOLN EX 2nd TO Cu PUR	SOLIDS EX 3rd	FILT EX 3rd TO Cu CEM	RTZ RESIDUE	SOLIDS EX 4th	FILT EX 4th TO 1st	Se/Te EX 4th	SOLIDS EX 5th	SOLN EX 5th	Se/Te EX Cu PUR	FEED TO Cu WIN	ELECT EX Cu WIN	Cu PRODUCT	NaHS	SO_2	H_2SO_4 leaches	H_2SO_4 nickel	EFFLUENT	FERROUS SULPHATE	H_2SO_4 utilities
ORIG UNITS	%	g/l	%	g/l&ppm	%	g/l	% & ppm	%	g/l&ppm	%	%	ppm	%	g/l&ppm	g/l&ppm	ppm&%	t	t	t	t	kl	t	t
Ni	0.82		5.2	336	0.00		7.73	0.18		0.004	0.209	0.003	0.316	340	345	0.058					7.89		
Cu	0.04		12.7	913	1.23		33.45	0.42	7.4	0.283	0.425	0.061	3.554	687	225	571					0.98		
Co	0.89	0.5	0.2	3			0.13							3	3						0.60		
Fe			3.1	9.2	0.04			0.23	0.23	0.002	0.326	0.001	0.032	8	9	0.010					0.05	0.28	
S	891.16									0.023	0.155		0.204			0.086	3.66	18.9	312	184	41.88	0.18	9

A3 (iii): OVERALL MASS BALANCE (based on average data)

(Note: Blanks indicate a lack of analysis information, except for S, where only the overall inputs and outputs are included).

UNIT OPERATION 1: COMMINUTION

ELEMENT	MATTE IN	WATER IN	MILLED MATTE OUT		UNIT No. 1 BALANCE
kg/h		225			
Ni	1020.63		1020.63		0.00
Cu	558.79		558.79		0.00
Co	6.90		6.90		0.00
Fe	12.71		12.71		0.00
S	421.77				

UNIT OPERATION 2: 1st STAGE LEACH & Cu CEMENTATION:

ELEMENT	MILLED MATTE IN	O_2 IN	SPENT ELECTR EX Cu IN	FILTRATE EX 4th STAGE IN	WATER IN	H_2SO_4 IN	3rd STAGE FILTRATE IN	Ni SULPHATE IN
kg/h		479			332	159		
Ni	1020.63		345.26					253.70
Cu	558.79		224.82	7.35				0.13
Co	6.90		2.79					1.71
Fe	12.71		9.08	0.23				4.29
S						52.4		188.14

ELEMENT	Co NITRATE SOLN IN	HNO_3 LEACH E/S EX Ni IN	AIR IN m^3/h	NaHS IN	FILTRATE TO JARO. OUT	SOLIDS TO 2nd STAGE LEACH	TOTAL IN	TOTAL OUT	UNIT No. 2 BALANCE
kg/h			3.00	6.42					
Ni	0.15	13.50			1129.22	228.34	1633.23	1357.57	275.66
Cu		0.00			0.03	951.50	791.11	951.53	-160.42
Co	2.01	0.04			9.66	1.55	13.44	11.21	2.23
Fe	1.93	0.00			15.31	5.77	28.23	21.07	7.16
S	6.33			3.66					

UNIT OPERATION 3: JAROSITE:

ELEMENT	FILTRATE EX Cu CEM IN	Fe SLURRY EX Co IN	Fe RES. EX Ni IN	WATER IN	O_2 IN	NH_3 IN	FILTRATE TO Ni PUR OUT	JARO RES OUT	TOTAL IN	TOTAL OUT		UNIT No. 3 BALANCE
				1161	3.56	70.7						
Ni	1129.22	0.32	0.00				1164.49	2.03	1129.54	1166.52		-36.98
Cu	0.03	0.00	0.00				0.02	0.03	0.03	0.05		-0.02
Co	9.66	0.37	0.00				9.96	0.03	10.03	9.99		0.04
Fe	15.31	0.00	0.00				0.05	21.19	15.31	21.24		-5.94
S								6.25				

UNIT OPERATION 4: Ni PURIFICATION & REDUCTION:

ELEMENT	FILTRATE FROM JARO IN	WATER IN	AIR IN m^3/h	NH_3 IN	H_2 IN	HNO_3 IN	FERROUS SULPHATE IN	BARREN LIQUOR EX MDS IN	Ni R/C EX Co IN	HNO_3 LEACH E/S TO Cu CEM OUT
kg/h		3518	0.96	873	99	84.5	1.39			
Ni	1164.49							2.39	46.68	13.50
Cu	0.02								0.00	0.00
Co	9.96							2.75	0.79	0.04
Fe	0.05						0.28		0.00	0.00
S							0.16			

ELEMENT	Ni PRODUCT OUT	Ni REDN SOLN TO MDS OUT	Fe SOLIDS TO JARO OUT	TOTAL IN	TOTAL OUT		UNIT No. 4 BALANCE
kg/h							
Ni	1362.12	66.49	0.00	1213.57	1442.10		-228.54
Cu	0.06	0.02	0.00	0.02	0.08		-0.06
Co	1.36	17.47	0.00	13.51	18.86		-5.35
Fe	0.10		0.00	0.33	0.10		0.23
S	0.14						

UNIT OPERATION 5: MIXED DOUBLE SALTS:

ELEMENT	Ni REDN END SOLN IN	H_2SO_4 IN	Co END SOLNS IN	AMM SUL Co PURGE SOLN IN	AMMONIA IN	MDS CAKE TO Co OUT	FEED TO AMM SUL OUT	BARREN LIQUOR TO Ni PUR OUT	TOTAL IN	TOTAL OUT	UNIT No. 5 BALANCE
kg/h		372			147						
Ni	66.49		0.00			2.39	1.52	2.39	66.49	6.30	60.19
Cu	0.02		0.00						0.02	0.00	0.02
Co	17.47		0.36	0.53		2.60	1.75	2.75	18.37	7.11	11.26
Fe			0.00			0.00			0.00	0.00	0.00
S		123									

UNIT OPERATION 6: Co PURIFICATION & REDUCTION:

ELEMENT	MDS CAKE IN	WATER IN	H_2SO_4 IN	AIR IN m^3/h	AMMONIA IN	O_2 IN	H_2 IN	RTZ Co CAKE IN	Ni RECYCLE TO Ni RED OUT	Fe SLURRY TO JARO OUT	Co END SOLNS TO MDS OUT	Co PRODUCT OUT	TOTAL IN	TOTAL OUT	UNIT No. 6 BALANCE
kg/h		228	151	0.051	104.9	4.75	0.745								
Ni	2.39							0.39	46.68	0.32	0.00	0.003	2.78	47.00	-44.22
Cu								0.02	0.00	0.00	0.00	0.000	0.02	0.00	0.02
Co	2.60							1.39	0.79	0.37	0.36	10.0	3.99	11.54	-7.55
Fe	0.00							0.05	0.00	0.00	0.00	0.000	0.05	0.00	0.05
S			49.7									0.001			

UNIT OPERATION 7: AMMONIUM SULPHATE:

ELEMENT	FEED EX MDS IN	Co PURGE SOLN TO MDS OUT	AMM SULPH PRODUCT OUT	TOTAL IN	TOTAL OUT		UNIT No. 7 BALANCE
Ni	1.52		0.82	1.52	0.82		0.71
Cu			0.04	0.00	0.04		-0.04
Co	1.75	0.53	0.89	1.75	1.42		0.33
Fe				0.00	0.00		0.00
S			891.16				

UNIT OPERATION 8: 2nd STAGE LEACH:

ELEMENT	SOLIDS EX 1st STAGE LEACH IN	WATER IN	O_2 IN	H_2SO_4 IN	RTZ RESIDUE IN	SOLIDS TO 3rd STAGE OUT	SOLUTION TO Cu PUR OUT	TOTAL IN	TOTAL OUT		UNIT No. 8 BALANCE
kg/h		4570	1099	792							
Ni	228.34				7.73	5.17	335.67	236.07	340.84		-104.77
Cu	951.50				33.45	12.66	913.44	984.94	926.10		58.84
Co	1.55				0.13	0.17	2.55	1.68	2.73		-1.05
Fe	5.77					3.11	9.17	5.77	12.28		-6.51
S				261							

UNIT OPERATION 9: 3rd STAGE LEACH:

ELEMENT	SOLIDS EX 2nd STAGE IN	WATER IN	H_2SO_4 IN	O_2 IN	FORMATE IN	SOLIDS TO 4th STAGE OUT	FILTRATE TO Cu CEMENT OUT	TOTAL IN	TOTAL OUT		UNIT No. 9 BALANCE
kg/h		209	19.1	35.6	17.2						
Ni	5.17					0.00		5.17	0.00		5.17
Cu	12.66					1.23		12.66	1.23		11.44
Co	0.17							0.17	0.00		0.17
Fe	3.11					0.04		3.11	0.04		3.07
S			6.30								

UNIT OPERATION 10: 4th STAGE LEACH:

ELEMENT	SOLIDS EX 3rd STAGE IN	WATER IN	H_2SO_4 IN	O_2 IN	SULPHUR DIOXIDE IN	Se/Te SOLIDS TOLL OUT	SOLIDS TO 5th STAGE OUT	FILTRATE TO 1st STAGE OUT	TOTAL IN	TOTAL OUT		UNIT No. 10 BALANCE
kg/h		142	37.7	16.6	2.98							
Ni	0.00					0.00	0.18		0.00	0.19		-0.19
Cu	1.23					0.28	0.42	7.35	1.23	8.05		-6.83
Co									0.00	0.00		0.00
Fe	0.04					0.00	0.23	0.23	0.04	0.46		-0.43
S			12.4		1.49	0.02						

UNIT OPERATION 11: 5th STAGE LEACH:

ELEMENT	SOLIDS EX 4th STAGE IN	WATER IN	CAUSTIC IN	O_2 IN	SOLIDS TO PMR OUT	FILTRATE TO PMR OUT	TOTAL IN	TOTAL OUT	UNIT No. 11 BALANCE
kg/h		48.0	12.5	0.078					
Ni	0.18				0.21	0.00	0.18	0.21	-0.03
Cu	0.42				0.43	0.06	0.42	0.49	-0.07
Co							0.00	0.00	0.00
Fe	0.23				0.33	0.00	0.23	0.33	-0.09
S					0.15				

UNIT OPERATION 12: Cu PURIFICATION:

ELEMENT	SOLN EX 2nd STAGE IN	WATER IN	SULPHUR DIOXIDE IN	Se/Te TOLL OUT	Cu SOLN TO WINN OUT	TOTAL IN	TOTAL OUT	UNIT No. 12 BALANCE
kg/h		56.0	34.8					
Ni	335.67			0.32	340.29	335.67	340.60	-4.93
Cu	913.44			3.55	686.79	913.44	690.35	223.09
Co	2.55				2.59	2.55	2.59	-0.04
Fe	9.17			0.03	8.47	9.17	8.50	0.67
S			17.4	0.20				

UNIT OPERATION 13: Cu ELECTROWINNING:

ELEMENT	SOLN EX Cu PUR IN	NH_3 IN	WATER IN	Cu CATHODE PRODUCT OUT	SPENT ELEC TO 1st STAGE OUT	TOTAL IN	TOTAL OUT	UNIT No. 13 BALANCE
kg/h		114	116					
Ni	340.29			0.06	345.26	340.29	345.31	-5.03
Cu	686.79			571.39	224.82	686.79	796.22	-109.43
Co	2.59				2.79	2.59	2.79	-0.19
Fe	8.47			0.01	9.08	8.47	9.09	-0.62
S				0.09				

ADDITIONAL STREAMS AND OVERALL MASS BALANCE:

ELEMENT	TOTAL EFFLUENT OUT	ADDITIONAL H_2SO_4 IN (Utilities)	SUM OF UNIT OP. INPUTS	SUM OF UNIT OP. OUTPUTS	DIFFERENCE	OVERALL % ERROR
Ni	7.69		5985.14	6075.78	-90.64	-7.1
Cu	0.98		3949.48	3933.91	15.57	2.6
Co	0.60		75.00	75.76	-0.76	-6.3
Fe	0.05		83.43	85.88	-2.45	-12.9
S	41.88	9	1152.9	939.9	213	18.5

APPENDIX 4

FULL PEMS LCI DATA, RELATING TO THE OVERALL AVERAGE BASE CASE.

NOTE: Values relate to the production of 1kg of nickel.

Abbreviations used:

Element: I = input
O = output

Type: I = Internal flows which remain within the system boundary
E = External flows: burdens associated with these flows are excluded
N = Flows to or from the natural environment, such as raw materials used and waste released to air.

Full Name	Flow Name	Unit	Element	Type	Total	01 BMR	02 H2 PRODUCTION	03 STEAM GENERATION	05 CO2	06 coal, hard UK	07 sastec	08 Effluent	09 PMR	10 Ash	11 natural gas delivered UK	12 oxygen from air decomposition	13 nitrogen from air decomposition	14 sulphuric acid	15 nitric acid	16 ammonia	17 PGM conc	18 Jarosite	19 Cu product	20 Co product	21 Ammonium sulphate	22 Barite	23 Matte inputs
Input	ammonia in	kg	I	I	0.9759	0.9759																					
Input	Ammonium sulphate in	kg	I	I	2.6818																				2.6818		
Input	Ash in	kg	I	I	1.2360									1.2360													
Input	Co product in	kg	I	I	0.0075																			0.0075			
Input	CO2 used in	kg	I	I	0.3207	0.1604			0.1603																		
Input	coal, hard UK in	kg	I	I	5.5976			5.5976																			
Input	Cu product in	kg	I	I	0.4263																		0.4263				
Input	Desmi to PMR in	kg	I	I	0.9414								0.9414														
Input	Effluent ex BMR in	kg	I	I	13.1542							13.1542															
Input	Effluent ex steam generation in	kg	I	I	0.7758							0.7758															
Input	H2 to PMR in	kg	I	I	0.0008								0.0008														
Input	Hydrogen used in	kg	I	I	0.0742	0.0742																					
Input	Jarosite in	kg	I	I	0.0587																	0.0587					
Input	Matte inputs to BMR in	kg	I	I	2.8319	2.8319																					
Input	natural gas delivered UK in	kg	I	I	0.6248		0.6248																				
Input	nitric acis (HNO3) in	kg	I	I	0.0629	0.0629																					
Input	nitrogen from air decomposition in	kg	I	I	0.5763	0.5763																					
Input	oxygen from air decomposition in	kg	I	I	1.2172	1.2172																					
Input	PGM concentrate in	kg	I	I	0.0677								0.0339								0.0339						
Input	Se/Te residue in	kg	I	I	0.0030																					0.0030	
Input	Steam to BMR in	kg	I	I	34.0476	34.0476																					
Input	Steam to H2 in	kg	I	I	4.7471		4.7471																				
Input	Steam to PMR in	kg	I	I	1.9603								1.9603														
Input	sulphuric acid (H2SO4) in	kg	I	I	1.1599	1.1599																					
Input	sastec in	MJ	I	I	24.0861	24.0861																					
Input	minor constituents (unspecified)	kg	I	E	0.0000						0.0000																
Input	processed water	kg	I	E	42.0609			42.0601			0.0008																
Input	Electricity (hydro)	MJ	I	E	0.0035						0.0035																
Input	Electricity (Nuclear)	MJ	I	E	0.0059						0.0059																
Input	air used (unspecified)	kg	I	N	19.1950		0.6527	12.2343			5.3221									0.9759							
Input	barite	kg	I	N	0.0036					0.0002					0.0016	0.0001	0.0001	0.0002	0.0000	0.0016							
Input	bauxite	kg	I	N	0.0011					0.0004	0.0000				0.0000	0.0002	0.0001	0.0002	0.0000	0.0001							
Input	bentonite	kg	I	N	0.0008					0.0003					0.0001	0.0001	0.0000	0.0001	0.0000	0.0002							
Input	Biotic reserves	kg	I	N	0.0001						0.0001																
Input	chromium reserves	kg	I	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Input	coal reserves (unspecified)	kg	I	N	2.4132						2.4132																
Input	cobalt reserves	kg	I	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Input	copper reserves	kg	I	N	0.0004					0.0001					0.0000	0.0001	0.0000	0.0001	0.0000	0.0000							
Input	gas reserves	kg	I	N	1.4618					0.0968	0.0001				0.6729	0.0131	0.0062	0.0482	0.0133	0.6111							
Input	hard coal reserves	kg	I	N	9.7522					9.5548					0.0086	0.0823	0.0390	0.0363	0.0008	0.0303							
Input	iron reserves	kg	I	N	0.0476					0.0312	0.0000				0.0056	0.0010	0.0005	0.0027	0.0002	0.0063							
Input	lead reserves	kg	I	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Input	lignite reserves	kg	I	N	0.2385					0.0000					0.0000	0.1082	0.0512	0.0445	0.0008	0.0337							
Input	limestone	kg	I	N	0.0699					0.0440	0.0000				0.0045	0.0033	0.0016	0.0105	0.0003	0.0056							
Input	manganese reserves	kg	I	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Input	molybdenum reserves	kg	I	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Input	nickel reserves	kg	I	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Input	O2	kg	I	N	3.1922					0.4261					0.1398	0.3629	0.1718	0.2958	0.0396	1.7563							

FullName	Flow Name	Unit	Element	Type	Total	01 BMR	02 H2 PRODUCTION	03 STEAM GENERATION	05 CO2	06 coal, hard UK	07 easiec	08 Effluent	09 PMR	10 Ash	11 natural gas delivered UK	12 oxygen from air decomposition	13 nitrogen from air decomposition	14 sulphuric acid	15 nitric acid	16 ammonia	17 PGM conc	18 Jarosite	19 Cu product	20 Co product	21 Ammonium sulphate	22 Sn/Te	23 Metric Inputs
Input	oil reserves	kg	I	N	0.1494					0.0396	0.0013				0.0239	0.0203	0.0096	0.0124	0.0009	0.0413							
Input	other inputs	kg	I	N	4.8735					0.0000	2.0416				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							2.8319
Input	palladium reserves	kg	I	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Input	platinum reserves	kg	I	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Input	reserves (unspecified)	kg	I	N	3.0164											1.2172	0.5763	1.1599	0.0629								
Input	rhenium reserves	kg	I	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Input	rhodium reserves	kg	I	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Input	silver reserves	kg	I	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Input	sodium chloride	kg	I	N	0.0004					0.0002	0.0000				0.0000	0.0001	0.0000	0.0001	0.0000	0.0000							
Input	tin reserves	kg	I	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Input	uranium reserves	kg	I	N	0.0000					0.0000	0.0000				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Input	water (unspecified)	kg	I	N	110.9933	21.0976				27.7177	12.2577	13.6435			0.9229	15.6538	7.4116	6.6152	0.1474	5.5157							
Input	wood	kg	I	N	0.1218					0.1174					0.0001	0.0015	0.0007	0.0014	0.0000	0.0006							
Input	zeolite	kg	I	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Input	zinc reserves	kg	I	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Input	land transformation II-III	m2a	I	N	0.1598					0.0484					0.0277	0.0235	0.0111	0.0125	0.0008	0.0357							
Input	land transformation II-IV	m2a	I	N	0.0209					0.0132					0.0026	0.0005	0.0003	0.0010	0.0001	0.0032							
Input	land transformation III-IV	m2a	I	N	0.0175					0.0070					0.0045	0.0003	0.0001	0.0013	0.0001	0.0042							
Input	land use IV-IV	m2a	I	N	0.0001					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Input	reservoir content	m3	I	N	0.0266					0.0025					0.0001	0.0110	0.0052	0.0045	0.0001	0.0034							
Input	turbine water	m3	I	N	563.2563					546.2269					12.0626	2.2534	1.0669	0.9281	0.0175	0.7009							
Input	process energy (biofuel)	MJ	I	N	1.9489					1.8791					0.0022	0.0238	0.0112	0.0221	0.0005	0.0100							
Input	process energy (hard coal)	MJ	I	N	291.5897					285.6900					0.2562	2.4613	1.1654	1.0863	0.0233	0.9072							
Input	process energy (hydro power)	MJ	I	N	1.1645					0.1155					0.0025	0.4747	0.2248	0.1960	0.0037	0.1474							
Input	process energy (lignite)	MJ	I	N	2.6904					0.0002					0.0002	1.2210	0.5781	0.5020	0.0095	0.3796							
Input	process energy (natural gas)	MJ	I	N	79.0905					5.2379					36.4120	0.7109	0.3366	2.5105	0.7185	33.0641							
Input	process energy (nuclear)	MJ	I	N	7.3150					1.4827					0.0324	2.6319	1.2462	1.0838	0.0204	0.8175							
Input	process energy (oil)	MJ	I	N	6.6655					1.7832					1.0773	0.9147	0.4331	0.5585	0.0411	1.8576							
Input	process energy (unspecified)	MJ	I	N	45.6528						45.6528																
Input	extracted energy (biofuel)	MJ (ex.)	I	N	1.9489					1.8791					0.0022	0.0238	0.0112	0.0221	0.0005	0.0100							
Input	extracted energy (hard coal)	MJ (ex.)	I	N	291.5897					285.6900					0.2562	2.4613	1.1654	1.0863	0.0233	0.9072							
Input	extracted energy (hydro power)	MJ (ex.)	I	N	1.1645					0.1155					0.0025	0.4747	0.2248	0.1960	0.0037	0.1474							
Input	extracted energy (lignite)	MJ (ex.)	I	N	2.6904					0.0002					0.0002	1.2210	0.5781	0.5020	0.0095	0.3796							
Input	extracted energy (natural gas)	MJ (ex.)	I	N	79.0905					5.2379					36.4120	0.7109	0.3366	2.5105	0.7185	33.0641							
Input	extracted energy (nuclear)	MJ (ex.)	I	N	7.3150					1.4827					0.0324	2.6319	1.2462	1.0838	0.0204	0.8175							
Input	extracted energy (oil)	MJ (ex.)	I	N	6.6655					1.7832					1.0773	0.9147	0.4331	0.5585	0.0411	1.8576							
Input	extracted energy (unspecified)	MJ (ex.)	I	N	67.6417						67.6417																
Output	ammonia	kg	O	I	0.9759															0.9759							
Output	Ammonium sulphate	kg	O	I	2.6816	2.6816																					
Output	Ash	kg	O	I	1.2300			1.2300																			
Output	Co product	kg	O	I	0.0075	0.0075																					
Output	CO2 used	kg	O	I	0.3207		0.1603		0.1603																		
Output	coal, hard UK	kg	O	I	5.5976					5.5976																	
Output	Cu product	kg	O	I	0.4263	0.4263																					
Output	Demin to PMR	kg	O	I	0.9415	0.9415																					
Output	Effluent ex BMR	kg	O	I	13.1568	13.1568																					

FullName	Flow Name	Unit	Element	Type	Total	01 BMR	02 H2 PRODUCTION	03 STEAM GENERATION	05 CO2	06 coal, hard UK	07 sxelec	08 Effluent	09 PMR	10 Ash	11 natural gas delivered UK	12 oxygen from air decomposition	13 nitrogen from air decomposition	14 sulphuric acid	15 nitric acid	16 ammonia	17 PGM conc	18 Jarosite	19 Cu product	20 Co product	21 Ammonium sulphate	22 SeTe	23 Matte inputs
Output	Effluent ex steam generation	kg	O	I	0.7758			0.7758																		
Output	H2 to PMR	kg	O	I	0.0008		0.0008																			
Output	Hydrogen used	kg	O	I	0.0742		0.0742																			
Output	Jarosite	kg	O	I	0.0587	0.0587																				
Output	Matte inputs to BMR	kg	O	I	2.8319																					2.8319
Output	natural gas delivered UK	kg	O	I	0.6248										0.6248											
Output	Ni product	kg	O	I	1.0000	1.0000																				
Output	nitric acid (HNO3)	kg	O	I	0.0629														0.0629							
Output	nitrogen from air decomposition	kg	O	I	0.5763												0.5763									
Output	oxygen from air decomposition	kg	O	I	1.2172											1.2172										
Output	PGM concentrate	kg	O	I	0.0677	0.0339															0.0339					
Output	SeTe residue	kg	O	I	0.0030	0.0030																				
Output	Steam to BMR	kg	O	I	34.0409			34.0409																		
Output	Steam to H2	kg	O	I	4.7471			4.7471																		
Output	Steam to PMR	kg	O	I	1.9603			1.9603																		
Output	sulphuric acid (H2SO4)	kg	O	I	1.1599													1.1599								
Output	sxelec	MJ	O	I	24.0861						24.0861															
Output	open loop outputs (unspecified)	kg	O	E	6.8612						0.0004		2.9364	0.8058									0.4263	0.0075	2.6818	0.0030
Output	solid waste (unspecified)	kg	O	E	4.0158					3.8343										0.1815						
Output	landfill volume (dm3)	dm3	O	N	1.1416						1.1416															
Output	radioactive (air)	kBq	O	N	1778.3947					360.2260					7.6919	640.0093	303.0277	263.2725	4.9586	199.0087						
Output	radioactive (water)	kBq	O	N	12.9813					0.0000					0.0000	5.8908	2.7691	2.4233	0.0457	1.8325						
Output	acetaldehyde	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
Output	acetic acid	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
Output	acetone	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
Output	acid (unspecified) (waterborne)	kg	O	N	0.0000						0.0000					0.0000	0.0000	0.0000	0.0000	0.0000						
Output	acrolein	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
Output	Ag (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
Output	Al	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
Output	Al (waterborne)	kg	O	N	0.0157					0.0154	0.0000				0.0000	0.0001	0.0001	0.0001	0.0000	0.0000						
Output	aldehydes (unspecified)	kg	O	N	0.0000					0.0000	0.0000				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
Output	alkali (unspecified) (waterborne)	kg	O	N	0.0000						0.0000															
Output	alkanes (unspecified)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
Output	alkanes (unspecified) (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
Output	alkenes (unspecified)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
Output	alkenes (unspecified) (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
Output	animal/vegetable oil	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
Output	aromatics (unspecified)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
Output	aromatics (unspecified) (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
Output	As	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
Output	As (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
Output	B	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
Output	B (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
Output	Ba	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
Output	Ba (waterborne)	kg	O	N	0.0013					0.0012					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
Output	barite (waterborne)	kg	O	N	0.0007					0.0000					0.0003	0.0000	0.0000	0.0000	0.0000	0.0003						
Output	Be	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
Output	Be (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
Output	benzaldehyde	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
Output	benzene	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						

FullName	Flow Name	Unit	Element	Type	Total	01 BMR	02 H2 PRODUCTION	03 STEAM GENERATION	05 CO2	06 coal, hard UK	07 coal,lig	08 Effluent	09 PMR	10 Ash	11 natural gas delivered UK	12 oxygen from air decomposition	13 nitrogen from air decomposition	14 sulphuric acid	15 nitric acid	16 ammonia	17 PGM conc	18 Jarosite	19 Cu product	20 Co product	21 Ammonium sulphate	22 Sorbe	23 Matte inputs
Output	benzene (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	benzo(a)pyrene	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Br2	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	butane (unspecified)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	butene	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Ca	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Ca (waterborne)	kg	O	N	0.0105					0.0100					0.0001	0.0001	0.0001	0.0001	0.0000	0.0001							
Output	Cd	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Cd (waterborne)	kg	O	N	0.0000					0.0000	0.0000				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	CFC (unspecified)	kg	O	N	0.0000						0.0000																
Output	chlorides (waterborne)	kg	O	N	0.1013					0.0963	0.0000				0.0008	0.0014	0.0007	0.0007	0.0000	0.0014							
Output	chlorobenzene (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Cl2	kg	O	N	0.0000						0.0000																
Output	CO	kg	O	N	0.0096					0.0005	0.0005				0.0002	0.0001	0.0000	0.0001	0.0001	0.0081							
Output	CO2 (non renewable)	kg	O	N	21.7985		0.8927	14.3650			6.5407																
Output	CO2 (renewable)	kg	O	N	0.0001						0.0001																
Output	CO2 (unspecified)	kg	O	N	2.3262					0.3906					0.1262	0.3326	0.1575	0.2711	0.0363	1.6099							
Output	cobalt	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	cobalt (waterborne)	kg	O	N	0.0005					0.0000		0.0005			0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Cr (unspecified)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Cr (unspecified) (waterborne)	kg	O	N	0.0000						0.0000																
Output	Cr-III (waterborne)	kg	O	N	0.0002					0.0002					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Cr-VI (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Cs (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Cu	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Cu (waterborne)	kg	O	N	0.0008					0.0001	0.0000	0.0007			0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	cyanide (bound) as CN (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	cyanides (unspecified)	kg	O	N	0.0000					0.0000	0.0000				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	DOCs (unspecified) (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	ethane	kg	O	N	0.0002					0.0000					0.0001	0.0000	0.0000	0.0000	0.0000	0.0002							
Output	ethanol	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	ethene	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	ethylbenzene	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	ethylbenzene (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	ethylene dichloride	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	ethyne	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	F2	kg	O	N	0.0000						0.0000																
Output	fatty acids (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Fe	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Fe (waterborne)	kg	O	N	0.0051					0.0046	0.0000				0.0000	0.0002	0.0001	0.0001	0.0000	0.0001							
Output	fluorides (waterborne)	kg	O	N	0.0000					0.0000	0.0000				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	formaldehyde	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	formaldehyde (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	glutaric aldehyde (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	H2S	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	H2S (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	halogenated HC (unspecified)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	halogenated HC (unspecified) (waterborne)	kg	O	N	0.0000					0.0000	0.0000				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							

FullName	Flow Name	Unit	Element	Type	Total	01 BMR	02 H2 PRODUCTION	03 STEAM GENERATION	05 CO2	06 coal, hard UK	07 sealoc	08 Effluent	09 PMR	10 Ash	11 natural gas delivered UK	12 oxygen from air decomposition	13 nitrogen from air decomposition	14 sulphuric acid	15 nitric acid	16 ammonia	17 PGM conc	18 Jarosite	19 Cu product	20 Co product	21 Ammonium sulphate	22 Salts	23 Matte inputs
Output	Inalon -1301	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	HC excl CH4 (unspecified)	kg	O	N	0.0000						0.0000																
Output	HCl	kg	O	N	0.0003					0.0001	0.0001				0.0000	0.0001	0.0000	0.0000	0.0000	0.0000							
Output	He	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	heptane	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	herbicides (unspecified)	kg	O	N	0.0000						0.0000																
Output	hexafluoroethane	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	hexane	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	HF	kg	O	N	0.0000					0.0000	0.0000				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Hg	kg	O	N	0.0000					0.0000	0.0000				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Hg (waterborne)	kg	O	N	0.0000					0.0000	0.0000				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	hydrocarbons (unspecified) (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	hydrogen	kg	O	N	0.0093		0.0093																				
Output	hypochlorous acid (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	insecticides (unspecified)	kg	O	N	0.0000						0.0000																
Output	iodides (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	iodine	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	K	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	K (waterborne)	kg	O	N	0.0048					0.0046					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	La	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	mercaptans/smell gas (unspecified)	kg	O	N	0.0000						0.0000																
Output	metals (unspecified)	kg	O	N	0.0000						0.0000																
Output	metals (unspecified) (waterborne)	kg	O	N	0.0004						0.0004																
Output	methane	kg	O	N	0.0893		0.0004			0.0800	0.0000				0.0020	0.0008	0.0004	0.0007	0.0001	0.0050							
Output	methanol	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	methyl tert-butyl ether	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	methyl tert-butyl ether (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Mg	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Mg (waterborne)	kg	O	N	0.0126					0.0123					0.0000	0.0001	0.0001	0.0000	0.0000	0.0000							
Output	mineral oil	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Mn	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Mn (waterborne)	kg	O	N	0.0003					0.0003					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Mo	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Mo (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	N (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	N2	kg	O	N	0.6047	0.5763	0.0279			0.0000					0.0002	0.0000	0.0000	0.0000	0.0000	0.0003							
Output	N2O	kg	O	N	0.0001					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Na	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Na (waterborne)	kg	O	N	0.0152					0.0130					0.0004	0.0005	0.0002	0.0003	0.0000	0.0007							
Output	NH3	kg	O	N	0.0022					0.0000	0.0001				0.0000	0.0000	0.0000	0.0000	0.0000	0.0020							
Output	Ni	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Ni (waterborne)	kg	O	N	0.0058					0.0001	0.0000	0.0057			0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	nitrates (waterborne)	kg	O	N	0.0000					0.0000	0.0000				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	nitrogen (organic bonded) (waterborne)	kg	O	N	0.0657					0.0656					0.0001	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	nitrogenous compounds (unspecified) (waterborne)	kg	O	N	0.1417					0.0000		0.1417			0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	non methane VOC (unspecified)	kg	O	N	0.0063					0.0005					0.0002	0.0002	0.0001	0.0001	0.0001	0.0052							
Output	NOx	kg	O	N	0.2593			0.2261		0.0020	0.0206				0.0006	0.0007	0.0003	0.0005	0.0002	0.0063							
Output	OCl- (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							

FullName	Flow Name	Unit	Element	Type	Total	01 BMR	02 H2 PRODUCTION	03 STEAM GENERATION	05 CO2	06 coal, hard UK	07 acetic	08 Effluent	09 PMR	10 Ash	11 natural gas delivered UK	12 oxygen from air decomposition	13 nitrogen from air decomposition	14 sulphuric acid	15 nitric acid	16 ammonia	17 PGM conc	18 Jarosite	19 Cu product	20 Co product	21 Ammonium sulphate	22 Barite	23 Matte inputs
Output	oils & greases (waterborne)	kg	O	N	0.0002					0.0000	0.0000				0.0001	0.0000	0.0000	0.0000	0.0000	0.0001							
Output	organic compounds (unspecified) (waterborne)	kg	O	N	0.0010					0.0000					0.0000	0.0000	0.0000	0.0001	0.0000	0.0009							
Output	other gases (unspecified)	kg	O	N	0.0001						0.0001																
Output	other solid (unspecified)	kg	O	N	1.0282						1.0282																
Output	P	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	P (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	PAH (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Pb	kg	O	N	0.0000					0.0000	0.0000				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Pb (waterborne)	kg	O	N	0.0001					0.0001	0.0000				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	pentane	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	pesticides (unspecified) (waterborne)	kg	O	N	0.0000						0.0000																
Output	phenol	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	phenols (unspecified)	kg	O	N	0.0000						0.0000																
Output	phenols (unspecified) (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	phosphates (waterborne)	kg	O	N	0.0009					0.0009	0.0000				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	polycyclic aromatic hydrocarbons (unspecified)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	propane	kg	O	N	0.0001					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	propene	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	propionaldehyde	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	propionic acid	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Pt	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Rb (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	residual landfill weight	kg	O	N	0.9720						0.9133											0.0587					
Output	salts (unspecified) (waterborne)	kg	O	N	0.0006					0.0000					0.0000	0.0004	0.0002	0.0002	0.0000	0.0001							
Output	Sb	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Sb (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Sc	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Se	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Se (waterborne)	kg	O	N	0.0001					0.0001					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Si	kg	O	N	0.0001					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Si (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Sn	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Sn (tributyl) (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Sn (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	SO2	kg	O	N	0.1221			0.0392		0.0023	0.0675				0.0005	0.0017	0.0008	0.0069	0.0001	0.0031							
Output	Sr	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Sr (waterborne)	kg	O	N	0.0002					0.0002					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	steam/water vapour	kg	O	N	37.9974	28.4925	4.8589	2.5055		0.1598	0.0001	0.9434			0.0524	0.1361	0.0644	0.1109	0.0149	0.6586							
Output	sulphates (waterborne)	kg	O	N	0.0975					0.0000	0.0000	0.0941			0.0000	0.0015	0.0007	0.0006	0.0000	0.0005							
Output	sulphides (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	sulphite (waterborne)	kg	O	N	0.0010					0.0000					0.0010	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	TDS (unspecified)	kg	O	N	0.0647					0.0063	0.0582				0.0000	0.0001	0.0000	0.0000	0.0000	0.0000							
Output	tetrachlorido-dibenzo-dioxin	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	tetrafluoromethane	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Th	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Tl	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Tl (waterborne)	kg	O	N	0.0009					0.0009					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Tl	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	toluene	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	toluene (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							

FullName	Flow Name	Unit	Element	Type	Total	01 SMR	02 H2 PRODUCTION	03 STEAM GENERATION	05 CO2	06 coal, hard UK	07 coke	08 Effluent	09 PKR	10 Ash	11 natural gas delivered UK	12 oxygen from air decomposition	13 nitrogen from air decomposition	14 sulphuric acid	15 nitric acid	16 ammonia	17 PGM cons	18 Jarosite	19 Cu product	20 Co product	21 Ammonium sulphate	22 Sulfo	23 Matte inputs
Output	trichloroethylene (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	TSP	kg	O	N	0.0150					0.0099	0.0020				0.0004	0.0005	0.0003	0.0009	0.0000	0.0010							
Output	TSS (unspecified)	kg	O	N	0.0018					0.0000	0.0018				0.0000												
Output	U	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	unsolved substances (waterborne)	kg	O	N	0.0024					0.0003	0.0000				0.0009	0.0001	0.0000	0.0001	0.0000	0.0010							
Output	V	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	V (waterborne)	kg	O	N	0.0001					0.0001					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	VOC	kg	O	N	0.0247						0.0247																
Output	W (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	waste water	kg	O	N	112.3266	7.8096				27.7177	13.3791	26.7294		0.4241	0.9229	15.6539	7.4116	5.8152	0.1474	5.5157							
Output	xylene (unspecified)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	xylene (waterborne)	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Zn	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Zn (waterborne)	kg	O	N	0.0002					0.0002	0.0000				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	Zr	kg	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	AOX	kg (ex.)	O	N	0.0000					0.0000					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	BOD	kg (ex.)	O	N	0.0000					0.0000	0.0000				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	COD	kg (ex.)	O	N	0.0000					0.0000	0.0000				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000							
Output	waste heat to air	MJ (ex.)	O	N	38.6597					8.2180					2.3844	7.0210	3.3242	5.4842	0.3579	11.9000							
Output	waste heat to soil	MJ (ex.)	O	N	0.4781					0.0397					0.0037	0.1972	0.0934	0.0812	0.0015	0.0615							
Output	waste heat to water	MJ (ex.)	O	N	0.5861					0.4426					0.0194	0.0919	0.0435	0.0393	0.0011	0.0482							
	Balance kg	kg	X	N	6.9519	7.0152	0.0001	0.0000	0.0000	0.0004	-0.0008	-0.3420	0.0000	0.0000	0.0440	0.1150	0.0549	0.0589	0.0040	0.0004	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	Balance MJ	MJ	X	N	436.1267	24.0961				295.1896	21.3782				37.7927	8.4384	3.9953	6.0592	0.8169	37.1834							

APPENDIX 5

EXAMPLES OF CLASSIFICATION CALCULATIONS.

A5 (I) EXAMPLES OF GREENHOUSE EFFECT CLASSIFICATION CALCULATIONS FOR THE AVERAGE BASE CASE

COMPOUND	CLASS. FACTOR	STEAM GENERATION			COAL			SA ELECTRICITY				
		kg/966.5t NI	kg/t NI	Impact score	kg/1000kg coal	kg/t NI	Impact score	kg/3600MJ	MJ/966.5t NI	MJ/t NI	kg/t NI	Impact score
INPUT QUANTITY (kg/t Ni)						5599			23279191	24086		
CO_2 (non renew)	1	13887000	14368	14368				978			6541	6541
CO_2 (renew)	1							0.0100			0.0669	0.0669
CO_2 (unspec)	1				69.8	391	391					
Dichloromethane	9											
Halogenated HC (unspec)	4											
Hexafluororethane	9200											
HFC (unspec)	1000											
Methane	21				14.3	80.0	1681	2.87E-04			0.00192	0.0403
N_2O	310				0.0300	0.168	52.1					
Tetrafluoromethane	6500											
Tetrafluoroethylene	1300											
Trichloromethane	4											
TOTAL (kg CO_2 per t NI)	23032			14368			2123					6541

A5 (II) EXAMPLES OF SMOG CLASSIFICATION CALCULATIONS FOR THE AVERAGE BASE CASE

Note: Only those compounds which were included in the relevant LCIs are shown here

COMPOUND	CLASS. FACTOR	STEAM GENERATION			COAL			SA ELECTRICITY				
		kg/966.5t NI	kg/t NI	Impact score	kg/1000kg coal	kg/t NI	Impact score	kg/3600MJ	MJ/966.5t NI	MJ/t NI	kg/t NI	Impact score
INPUT QUANTITY (kg/t Ni)						5599			23279191	24086		
Butane (unspec)	0.315				0.00100	0.00560	0.00176					
Ethane	0.082				0.00100	0.00560	0.000459					
Methane	0.007				14.3	80.0	0.560					
Non methane VOC (unspec)	0.416				0.0860	0.481	0.200					
Pentane	0.352				0.00100	0.00560	0.00197					
Propane	0.42				0.00100	0.00560	0.00235					
VOC	0.377							3.688			24.7	9.30
Xylene (unspec)	0.849				0.00100	0.00560	0.00475					
TOTAL (kg ethene per t NI)	10.1			0			0.772					9.30
NOx	1	200000	228	228	0.361	2.02	2.02	3.078			20.6	20.6
TOTAL (kg NOx per t NI)	251			228			2.02					20.6

A5(III) EXAMPLES OF RESOURCE DEPLETION CLASSIFICATION CALCULATIONS FOR THE AVERAGE BASE CASE

COMPOUND	CLASS. FACTOR	STEAM GENERATION			COAL			SA ELECTRICITY				
		kg/966.5t Ni	kg/t Ni	Impact score	kg/1000kg coal	kg/t Ni	Impact score	kg/3600MJ	MJ/966.5t Ni	MJ/t Ni	kg/t Ni	Impact score
INPUT QUANTITY (kg/t Ni)						5599			23279191	24086		
Antimony reserves	0.0128											
As reserves	0.0476											
Asbestos reserves	0.037											
Barite	0.0333				0.0400	0.224	0.00746					
Bauxite	0.0045				0.0770	0.431	0.00194					
Bi reserves	0.0357											
B reserves	0.0034											
Cd reserves	0.037											
Cr reserves	0.0095				0.00400	0.0224	0.000213					
Coal res. (unspec)	0.0026							361			2413	6.27
Co reserves	0.0111											
Cu reserves	0.0278				0.0240	0.134	0.00374					
Fluorspar	0.0192											
Fossil reserves	0.025											
Gas reserves	0.0167				17.3	96.8	1.62	0.0220			0.147	0.00246
Au reserves	0.0455											
Hard coal (reserves)	0.0026				1707	9557	24.8					
In reserves	0.0588											
Industrial diamonds	0.0556											
Fe reserves	0.0084				5.57	31.2	0.262					
Pb reserves	0.05											
Lignite reserves	0.0026											
Mn reserves	0.0105				0.00400	0.0224	0.000235					
Hg reserves	0.04											
Mb reserves	0.02											
Ni reserves	0.0182				0.00100	0.00560	0.000102					
Oil reserves	0.025				7.08	39.6	0.991	0.195			1.30	0.0326
Pt reserves	0.0051											
Potash	0.0033											
Rh reserves	0.0114											
Se reserves	0.0244											
Ag reserves	1											
S reserves	0.0417											
Talc	0.0217											
Tantalum reserves	0.0133											
Te reserves	0.0098											
Sn reserves	0.0357											
Ti reserves	0.0143											
Tungsten reserves	0.0182											
U reserves	0.0172				0.00100	0.00560	9.63E-05					
V reserves	0.0074											
Vermiculite	0.0123											
Zn reserves	0.0476											
Zr reserves	0.0182											
TOTAL (per year & per t Ni)	34.0			0			27.7					6.31

A5 (iv) EXAMPLES OF GREENHOUSE EFFECT CLASSIFICATION CALCULATIONS FOR 10/95 (low Ni production)

10/95: 533.6t Ni produced

COMPOUND	CLASS. FACTOR	STEAM GENERATION			COAL			SA ELECTRICITY				
		kg/533.6t Ni	kg/t Ni	Impact score	kg/1000kg coal	kg/t Ni	Impact score	kg/3600MJ	MJ/533.6t Ni	MJ/t Ni	kg/t Ni	Impact score
INPUT QUANTITY (kg/t Ni)						4660			20553307	38518		
CO_2 (non renew)	1	11959000	22412	22412				978			10460	10460
CO_2 (renew)	1							0.0100			0.107	0.107
CO_2 (unspec)	1				69.8	325	325					
Dichloromethane	9											
Halogenated HC (unspec)	4											
Hexafluororethane	9200											
HFC (unspec)	1000											
Methane	21				14.3	66.6	1399	2.87E-04			0.00307	0.0644
N_2O	310				0.0300	0.140	43.3					
Tetrafluoromethane	6500											
Tetrafluoroethylene	1300											
Trichloromethane	4											
TOTAL (kg CO_2 per t Ni)	**34639**			22412			1767					10460

A5 (v) EXAMPLES OF SMOG CLASSIFICATION CALCULATIONS FOR 10/95 (low Ni production)

10/95: 533.6t Ni produced
Note: Only those compounds which were included in the relevant LCIs are shown here

COMPOUND	CLASS. FACTOR	STEAM GENERATION			COAL			SA ELECTRICITY				
		kg/533.6t Ni	kg/t Ni	Impact score	kg/1000kg coal	kg/t Ni	Impact score	kg/3600MJ	MJ/533.6t Ni	MJ/t Ni	kg/t Ni	Impact score
INPUT QUANTITY (kg/t Ni)						4660			20553307	38518		
Butane (unspec)	0.315				0.00100	0.00466	0.00147					
Ethane	0.082				0.00100	0.00466	0.000382					
Methane	0.007				14.3	66.6	0.466					
Non methane VOC (unspec)	0.416				0.0860	0.401	0.167					
Pentane	0.352				0.00100	0.00466	0.00164					
Propane	0.42				0.00100	0.00466	0.00196					
VOC	0.377							3.688			39.5	14.88
Xylene (unspec)	0.849				0.00100	0.00466	0.00396					
TOTAL (kg ethene per t Ni)	**15.52**			0			0.642					14.88
NOx	1	189862	356	356	0.361	1.68	1.68	3.078			32.9	32.9
TOTAL (kg NOx per t Ni)	**391**			356			1.68					32.9

A5 (vi) EXAMPLES OF RESOURCE DEPLETION CLASSIFICATION CALCULATIONS FOR 10/95 (low Ni production)

10/95: 533.6t Ni produced

COMPOUND	CLASS. FACTOR	STEAM GENERATION			COAL			SA ELECTRICITY				
		kg/533.6t Ni	kg/t Ni	Impact score	kg/1000kg coal	kg/t Ni	Impact score	kg/3600MJ	MJ/533.6t Ni	MJ/t Ni	kg/t Ni	Impact score
INPUT QUANTITY (kg/t Ni)						4660			20553307	38518		
Antimony reserves	0.0128											
As reserves	0.0476											
Asbestos reserves	0.037											
Barite	0.0333				0.0400	0.186	0.00621					
Bauxite	0.0045				0.0770	0.359	0.00161					
Bi reserves	0.0357											
B reserves	0.0034											
Cd reserves	0.037											
Cr reserves	0.0095				0.00400	0.0186	0.000177					
Coal res. (unspec)	0.0026							361			3859	10.0
Co reserves	0.0111											
Cu reserves	0.0278				0.0240	0.112	0.00311					
Fluorspar	0.0192											
Fossil reserves	0.025											
Gas reserves	0.0167				17.3	80.6	1.35	0.0220			0.235	0.00393
Au reserves	0.0455											
Hard coal (reserves)	0.0026				1707	7954	20.7					
In reserves	0.0588											
Industrial diamonds	0.0556											
Fe reserves	0.0084				5.57	25.9	0.218					
Pb reserves	0.05											
Lignite reserves	0.0026											
Mn reserves	0.0105				0.00400	0.0186	0.000196					
Hg reserves	0.04											
Mb reserves	0.02											
Ni reserves	0.0182				0.00100	0.00466	0.0000848					
Oil reserves	0.025				7.08	33.0	0.825	0.195			2.09	0.0522
Pt reserves	0.0051											
Potash	0.0033											
Rh reserves	0.0114											
Se reserves	0.0244											
Ag reserves	1											
S reserves	0.0417											
Talc	0.0217											
Tantalum reserves	0.0133											
Te reserves	0.0098											
Sn reserves	0.0357											
Ti reserves	0.0143											
Tungsten reserves	0.0182											
U reserves	0.0172				0.00100	0.00466	8.02E-05					
V reserves	0.0074											
Vermiculite	0.0123											
Zn reserves	0.0476											
Zr reserves	0.0182											
TOTAL (per year & per t Ni)	**33.2**			0			23.1					10.1

A5 (vii) EXAMPLES OF GREENHOUSE EFFECT CLASSIFICATION CALCULATIONS FOR 4/97 (high Ni production)

4/97: 1356t Ni prod

COMPOUND	CLASS. FACTOR	STEAM GENERATION			COAL			SA ELECTRICITY				
		kg/1356t Ni	kg/t Ni	Impact score	kg/1000kg coal	kg/t Ni	Impact score	kg/3600MJ	MJ/1356t Ni	MJ/t Ni	kg/t Ni	Impact score
INPUT QUANTITY (kg/t Ni)						6066			26856331	19806		
CO_2 (non renew)	1	15567000	11480	11480				978			5378	5378
CO_2 (renew)	1							0.0100			0.0550	0.0550
CO_2 (unspec)	1				69.8	423	423					
Dichloromethane	9											
Halogenated HC (unspec)	4											
Hexafluororethane	9200											
HFC (unspec)	1000											
Methane	21				14.3	86.7	1821	2.87E-04			0.00158	0.0331
N_2O	310				0.0300	0.182	56.4					
Tetrafluoromethane	6500											
Tetrafluoroethylene	1300											
Trichloromethane	4											
TOTAL (kg CO_2 per t Ni)	**19159**			11480			2301					5378

A5 (viii) EXAMPLES OF SMOG CLASSIFICATION CALCULATIONS FOR 4/97 (high Ni production)

4/97: 1356t Ni prod
Note: Only those compounds which were included in the relevant LCIs are shown here

COMPOUND	CLASS. FACTOR	STEAM GENERATION			COAL			SA ELECTRICITY				
		kg/1356t Ni	kg/t Ni	Impact score	kg/1000kg coal	kg/t Ni	Impact score	kg/3600MJ	MJ/1356t Ni	MJ/t Ni	kg/t Ni	Impact score
INPUT QUANTITY (kg/t Ni)						6066			26856331	19806		
Butane (unspec)	0.315				0.00100	0.00607	0.00191					
Ethane	0.082				0.00100	0.00607	0.000497					
Methane	0.007				14.3	86.7	0.607					
Non methane VOC (unspec)	0.416				0.0860	0.522	0.217					
Pentane	0.352				0.00100	0.00607	0.00214					
Propane	0.42				0.00100	0.00607	0.00255					
VOC	0.377							3.688			20.3	7.65
Xylene (unspec)	0.849				0.00100	0.00607	0.00515					
TOTAL (kg ethene per t Ni)	**8.5**			0			0.836					7.65
NOx	1	247146	182	182	0.361	2.19	2.19	3.078			16.9	16.9
TOTAL (kg NOx per t Ni)	**201**			182			2.19					16.9

A5 (Ix) EXAMPLES OF RESOURCE DEPLETION CLASSIFICATION CALCULATIONS FOR 4/97 (high Ni production)

4/97: 1356t Ni prod

COMPOUND	CLASS. FACTOR	STEAM GENERATION			COAL				SA ELECTRICITY			
		kg/1356t Ni	kg/t Ni	Impact score	kg/1000kg coal	kg/t Ni	Impact score	kg/3600MJ	MJ/1356t Ni	MJ/t Ni	kg/t Ni	Impact score
INPUT QUANTITY (kg/t Ni)						6066			26856331	19806		
Antimony reserves	0.0128											
As reserves	0.0476											
Asbestos reserves	0.037											
Barite	0.0333				0.0400	0.243	0.00808					
Bauxite	0.0045				0.0770	0.467	0.00210					
Bi reserves	0.0357											
B reserves	0.0034											
Cd reserves	0.037											
Cr reserves	0.0095				0.00400	0.0243	0.000231					
Coal res. (unspec)	0.0026							361			1984	5.16
Co reserves	0.0111											
Cu reserves	0.0278				0.0240	0.146	0.00405					
Fluorspar	0.0192											
Fossil reserves	0.025											
Gas reserves	0.0167				17.3	104.9	1.75	0.0220			0.121	0.00202
Au reserves	0.0455											
Hard coal (reserves)	0.0026				1707	10354	26.9					
In reserves	0.0588											
Industrial diamonds	0.0556											
Fe reserves	0.0084				5.57	33.8	0.284					
Pb reserves	0.05											
Lignite reserves	0.0026											
Mn reserves	0.0105				0.00400	0.0243	0.000255					
Hg reserves	0.04											
Mb reserves	0.02											
Ni reserves	0.0182				0.00100	0.00607	0.000110					
Oil reserves	0.025				7.08	42.9	1.074	0.195			1.07	0.0268
Pt reserves	0.0051											
Potash	0.0033											
Rh reserves	0.0114											
Se reserves	0.0244											
Ag reserves	1											
S reserves	0.0417											
Talc	0.0217											
Tantalum reserves	0.0133											
Te reserves	0.0098											
Sn reserves	0.0357											
Ti reserves	0.0143											
Tungsten reserves	0.0182											
U reserves	0.0172				0.00100	0.00607	1.04E-04					
V reserves	0.0074											
Vermiculite	0.0123											
Zn reserves	0.0476											
Zr reserves	0.0182											
TOTAL (per year & per t Ni)	**35.2**			0			30.0					5.19