



National Pollutant Inventory

Emission Estimation Technique Manual

for

**Gold Ore Processing
Version 1.1**



*First published in May 1999
Version 1.1 – 9 October 2001*

ISBN: 0 6425 46991

www.npi.gov.au

© Commonwealth of Australia 2001

This manual may be reproduced in whole or part for study or training purposes subject to the inclusion of an acknowledgment of the source. It may be reproduced in whole or part by those involved in estimating the emissions of substances for the purpose of National Pollutant Inventory (NPI) reporting. The manual may be updated at any time. Reproduction for other purposes requires the written permission of Environment Australia, GPO Box 787, Canberra, ACT 2601, e-mail npi@ea.gov.au, internet address www.npi.gov.au or phone 1800 657 945.

Disclaimer

The manual was prepared in conjunction with Australian States and Territories according to the National Environment Protection (National Pollutant Inventory) Measure.

While reasonable efforts have been made to ensure the contents of this manual are factually correct, the Commonwealth does not accept responsibility for the accuracy or completeness of the contents and shall not be liable for any loss or damage that maybe occasioned directly or indirectly through the use of, or reliance on, the contents of this manual.

Erratum for Gold Ore Processing EET Manual (Version 1.1 – October 2001).

Page	Outline of alteration
1	Changed version number, added EA logo and amended footer to make document consistent with other EET Manuals
1	ANZSIC code and some introductory information changed from previous version.

**EMISSION ESTIMATION TECHNIQUES
FOR
GOLD ORE PROCESSING**

TABLE OF CONTENTS

DISCLAIMER	i
ERRATUM FOR GOLD ORE PROCESSING EET	ii
1.0 INTRODUCTION	1
2.0 PROCESS DESCRIPTION	5
3.0 LIKELY EMISSIONS	9
3.1 Reporting Thresholds	11
3.1.1 Category 1	11
3.1.2 Category 1a	11
3.1.3 Category 2a	11
3.1.4 Category 2b	12
3.1.5 Category 3	12
4.0 EMISSION ESTIMATION	13
4.1 Elements of the Environment	18
4.1.1 Emissions to Air.....	18
4.1.2 Emissions to Water	18
4.1.3 Emissions to Land.....	19
5.0 MASS BALANCE	20
5.1 Water Balance	20
5.2 Cyanide Balance	21
5.2.1 Cyanide Emissions from Storage and Mixing Areas	23
5.2.2 Cyanide Emissions from the Ore Processing Area (Leaching, Flotation & Smelting)	23
5.2.3 Cyanide Emissions from TSFs.....	23
5.2.4 Cyanide Emissions from Heap/Dump Leaches	26
5.3 Metals	27
5.4 Chemical Usage	28
5.5 Roaster and Smelter Emissions	29
5.5.1 Emissions Estimation for Roaster and Smelter operations	29
5.5.2 Emissions Estimation for Fuel	29
6.0 EMISSION FACTORS	30
6.1 Carbon Disulfide	31
6.2 Cyanide	32
6.2.1 Cyanide Emissions from the Ore Processing Area	33
6.2.2 Cyanide Emissions from the TSFs.....	33
6.3 Dust: PM₁₀ and Total Suspended Particulates (TSP)	34
6.4 Metals in Dust	35
6.5 Sewage	37
6.6 Combustion Emissions	38
6.7 Carbon Regeneration	38
6.8 Fuel Storage	38
7.0 MODELLING	39

7.1	Groundwater Modelling - Fates & Trajectories.....	39
7.2	Seepage from TSFs.....	39
7.3	Cyanide.....	40
8.0	ENGINEERING CALCULATIONS	41
9.0	DIRECT MEASUREMENT OR SOURCE MONITORING	42
9.1	Total Nitrogen and Total Phosphorus.....	42
9.2	Dust & PM ₁₀	43
9.3	Metals in Dust.....	43
9.4	Cyanide.....	43
9.5	TSF Seepage.....	44
10.0	EMISSION FACTOR RATING	47
11.0	DEFINITIONS	48
12.0	REFERENCES	49
12.1	References Cited in Text.....	49
12.2	References Not Cited in Text.....	49

APPENDICES

Appendix A - Generic Ore Assays	51
Appendix B - Existing Data	54
Appendix C - Transfers	59
Appendix D - Example Emissions Calculations	61

GOLD ORE PROCESSING

LIST OF FIGURES AND TABLES

Figure 1 - Scope of the 'Gold Ore Processing EET Manual' and its Relationship with other EET Manuals	2
2 - Gold Ore Processing: Process Inputs and Emissions	6
3 - CIP Counter Current Flow	7
4 - TSF Water Balance.....	20
5 - Cyanide Balance.....	22
6 - Mass Balance of Cyanide Emissions from TSFs.....	24
7 - Mass Balance of Cyanide from Heap/Dump Leaches	26
8 - Mass Balance for Smelter and Converter Operations.....	29
9 - TSF Bore Hole Monitoring Approach	45
Table 1 - NPI-Listed Substances Likely to Trigger Reporting Thresholds, and Proposed Methods for Determining Emissions.	10
2 - Relevant NPI-Listed Substances for the Gold Ore Processing Industry, and Recommended EETs	15
3 - Effect of pH on the Volatilisation of Cyanide	34
4 - Emission Factors for Dust Generation.....	36
5 - Indicative Pollution Figures for Wastewater NPI Threshold Tripping.....	37

1.0 Introduction

The purpose of all Emission Estimation Technique (EET) Manuals in this series is to assist Australian manufacturing, industrial, and service facilities to report emissions of listed substances to the National Pollutant Inventory (NPI). This Manual describes the procedures and recommended approaches for estimating emissions from facilities engaged in gold ore processing.

The scope of this document is to outline methods that can be used by the gold ore processing industry to:

- identify which substances they are required to report as part of the National Pollutant Inventory (NPI); and
- estimate emissions of NPI substances to air, water and land from their facilities.

This manual covers the processing of gold ore commencing from the delivery of raw ore to the mills, to the production of mine bars (or gold doré).

The emission of NPI substances from a processing facility's Tailings Storage Facilities (TSFs), waste management sites and sewerage systems are included in the reporting requirements of the NPI system, and are covered by this manual.

EET MANUAL: Gold Ore Processing

HANDBOOK: Precious Metal Manufacturing: Gold Ore Processing

ANZSIC CODE : 1314

This manual does not cover the extraction of ore. Extractive mining operations are covered by the *EET Manual for Mining*.

This manual does not cover gold refining which will be incorporated into the Non-Ferrous Metal Manufacture EET manual in the future.

The scope of this manual is presented diagrammatically in Figure 1.

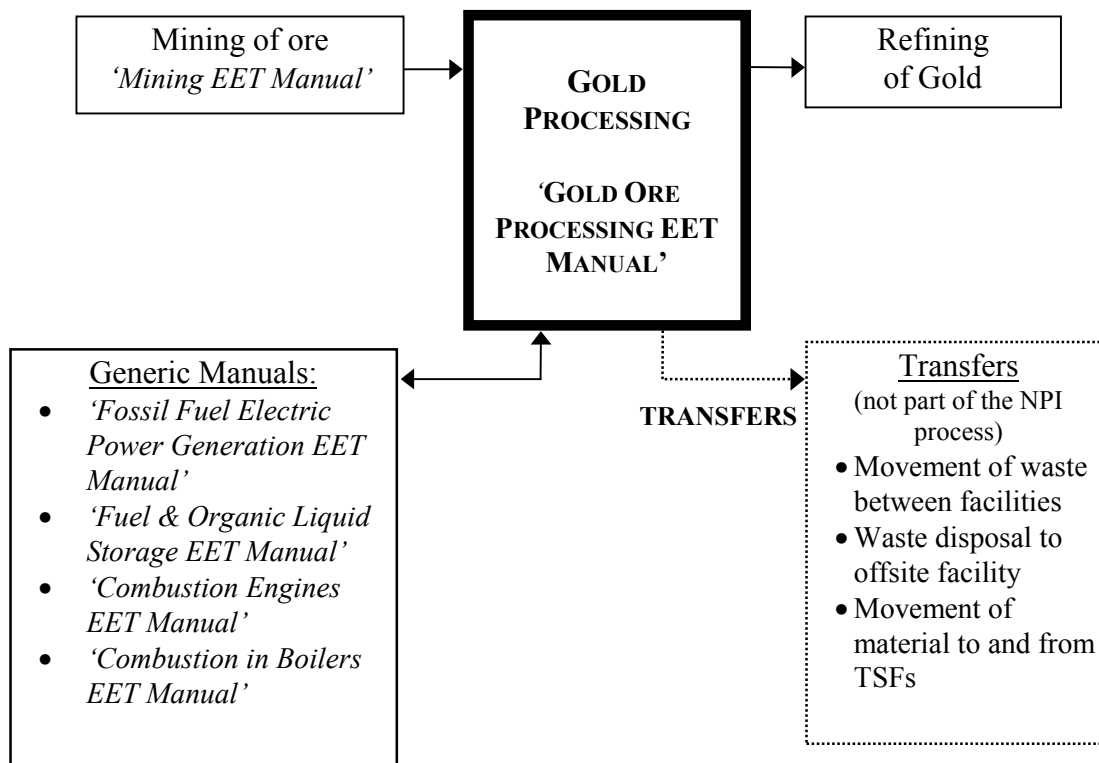


Figure 1 - Scope of the 'Gold Ore Processing EET Manual' and its Relationship with other EET Manuals

Context and use of the manual

The NPI manual provides a “how to” guide for the application of various methods to estimate emissions as required by the NPI. It is recognised that the data generated in this process will have varying degrees of accuracy with regards to the actual emissions from gold processing facilities. In some cases there will potentially be a large error due to inherent assumptions in the various emission estimation techniques (EETs) and/or a lack of knowledge of chemical processes or site-specific conditions.

This difficulty is well illustrated by the example of emissions of cyanide from tailings storage facilities. Research in this area undertaken by the WA Chemistry Centre has shown that, for two tailings storage facilities (TSFs) with similar rates of leakage to groundwater, there was no movement of cyanide into groundwater at one site, while significant contamination of groundwater was detected for the second site.

This dramatic difference was believed to be a result of the particular site characteristic such as cyanide speciation, mineralogy and pH.

EETs should be considered as 'points of reference'

The EETs and generic emission factors presented in the manual should be seen as ‘points of reference’ for guidance purposes only. Each has associated error bands that are potentially quite large ie. based on generic emission factors only, uncertainties of 100% are considered likely. Chapter 10 discusses the general reliability associated with the various methods. The potential errors associated with the different EET options should be considered on a case-by-case basis as to

their suitability for a particular facility. Facilities are not obligated to use the techniques presented in this manual. They must, however, seek the consent of their relevant environmental authority to determine whether any 'in house' EETs are suitable for meeting their NPI reporting requirements.

Hierarchical approach recommended in applying EETs

The manual presents a number of different EETs, each of which could be applied to the estimation of NPI substances. The range of available methods should be viewed as a hierarchy of available techniques in terms of the error associated with the estimate. Each substance needs to be considered in terms of the level of error that is acceptable or appropriate with the use of the various estimation techniques. Also the availability of pre-existing data and the effort required to decrease the error associated with the estimate will need to be considered. For example, if emissions of a substance are clearly very small no matter which EET is applied, then there would be little gained by applying an EET which required significant additional sampling.

The steps in meeting the reporting requirements of the NPI can be summarised as follows:

- for Category 1 and 1a substances, identify which reportable NPI substances are used (or handled by way of their incidental presence in ore or materials, or exceeds the bulk storage capacity for 1a), and determine whether the amounts used, or handled, are above the threshold limits and therefore trigger reporting requirements;
- for Category 2a and 2b substances, determine the amount and rate of fuel (or waste) burnt each year, the annual power consumption and the maximum potential power consumption, and assess whether the threshold limits are exceeded;
- for Category 3 substances determine the annual emissions to water and assess whether the threshold limits are exceeded; and
- for those substances above the threshold limits, examine the available range of EETs and determine emission estimates using the most appropriate EET.

Generally it will be appropriate to consider various EETs as alternative options whose suitability should be evaluated in terms of:

- the associated reliability or error bands; and
- the cost/benefit of using a more reliable method.

A general 'reliability' rating of methods is discussed in Chapter 10 - Emission Factor Rating.

NPI emissions in the environmental context

You should note that the NPI reporting process generates emission estimates only. It does not distinguish between the potential environmental impacts, bioavailability of emissions or natural background levels of these emissions.

The manual is structured to allow facilities to work through the manual addressing issues in a structured and coherent manner.

Likely emissions from facilities are discussed in Section 3, while Section 4 discusses the approach to emission estimation and those elements of the environment where emissions may result.

Sections 5, 6, 7, 8 and 9 address the EETs likely to be used by the gold industry. This approach has been adopted in order to demonstrate how an EET may be applied to estimating emissions of a substance and supported by other EETs. For example facilities may choose to use a mass balance approach to their estimation of cyanide emissions. However, the mass balance EET is likely to be supported by direct monitoring data and emission factors.

This manual has been prepared by PPK Environment & Infrastructure Pty Ltd on behalf of the WA Department of Environmental Protection. Funding for the project was provided by Environment Australia. It has been developed through a process of national consultation involving State and Territory environmental authorities, and industry groups.

2.0 Process Description

In Australia, there is variety of methods for gold ore processing used at different facilities. At most facilities, a key step is the extraction of gold from the crushed ore using cyanide and carbon adsorption. This can be done using carbon in pulp (CIP) and carbon in leach (CIL) processes where the gold-cyanide complex binds preferentially to activated carbon. Zinc dust is used as an alternative to carbon at some facilities.

Other processing methods include heap leaching of low-grade ores. Biological oxidation and roasting may be undertaken at some sites where gold is bound up in sulfide ores. These processes free up the gold from the sulfide ores by converting them to oxides.

Figure 2 presents a simplified flow diagram of various gold ore processing technologies used in Australia. The diagram is not intended to represent the processes undertaken at particular facilities. It is intended to provide an understanding of the main gold ore processing technologies and their associated inputs and emissions.

Facilities will have their own process flow diagrams and these should be used to facilitate emission estimation and NPI reporting requirements.

Gold ore processing includes the following steps.

Comminution. The process of reducing the ore to fine particles through crushing and milling. Crushing is the process whereby mined ore is fed through mechanical crushing devices that progressively reduce the size of the ore. Milling is a physical process where the crushed ore is fed into a mill (ie. rotating drums) and the action of the ore being tumbled (often in the presence of steel mill balls) reduces the ore to a slurry of fine particles.

Flotation. The process used to separate gold and metal sulfides from the gangue (ie. waste). Aeration of the milled slurry, and the addition of specific chemical reagents, encourages froth formation, while activators are added to promote flotation of gold-bearing compounds. The froth that floats to the surface contains most of the gold and iron sulfides, and is extracted for further treatment. This material is known as the concentrate.

Thickening. Thickening reduces the water content of the concentrate slurry, separating the water from the heavier mineral-rich solids through gravity.

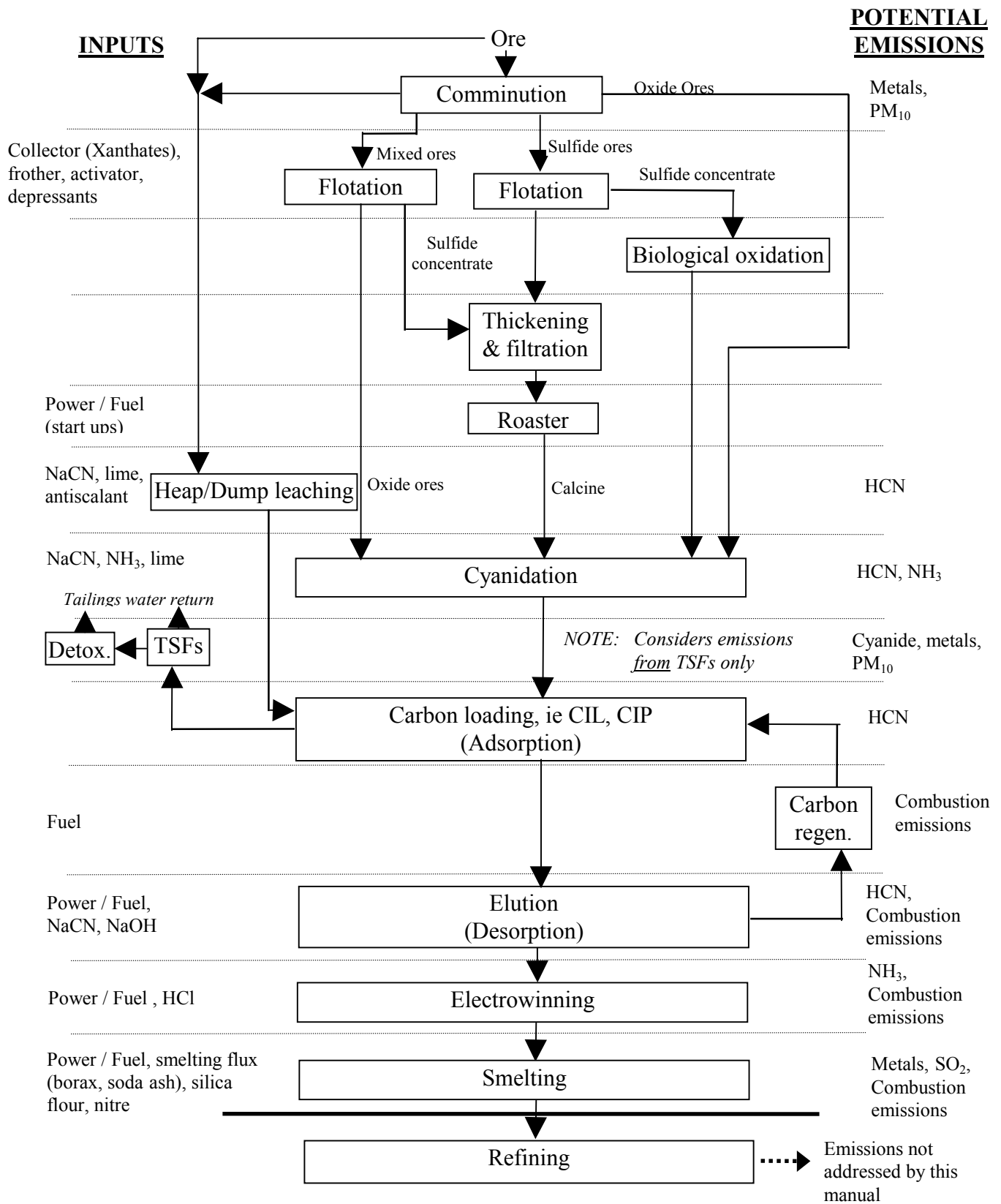


Figure 2 - Gold Ore Processing: Process Inputs and Emissions

Roasting. Where gold is trapped in sulfides such as pyrite, roasting of the concentrate is required to convert the sulfides to oxides (called calcine), with sulfides liberated as sulfur dioxide. Oxidation is necessary for the subsequent gold leaching and recovery processes to operate effectively.

Biological Oxidation. This is an alternative method for the oxidation of sulfides. Recent advances in technology have resulted in the development of a biological process for the oxidation of sulfide concentrates. In this process bacteria are used to oxidise sulfide concentrates.

Cyanidation. Cyanide is added to the process slurry to promote the dissolution and complexing of the gold. Gold enters solution as a gold-cyanide complex ion.

Carbon-In-Pulp (CIP). CIP involves the removal of complex gold ions from solution by adsorption onto activated carbon. A slurry that has undergone cyanidation is passed through a cascade of agitation tanks. As the slurry moves down the cascade, gold is adsorbed onto granular activated carbon that is extracted and pumped to the next tank. The result is a counter-current flow (as Figure 3), where the loading of gold on carbon increases in the opposite direction to slurry flow. Loaded carbon is retrieved from the first tank in the series.

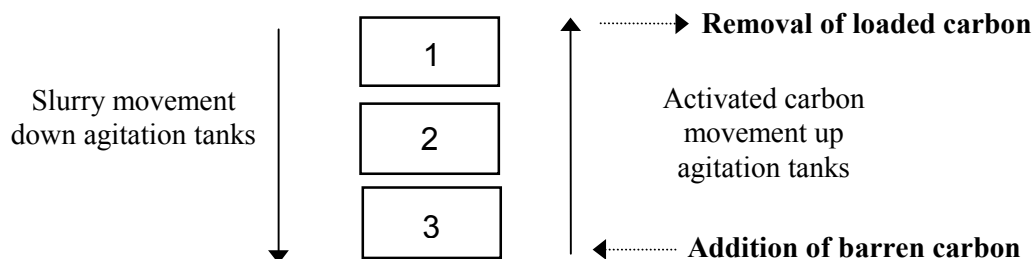


Figure 3 - CIP Counter Current Flow

Carbon-In-Leach (CIL). An alternative process to CIP. The main difference between the processes is that the cyanidation and adsorption processes are not staged separately, so that gold dissolution and recovery from the slurry proceed simultaneously in each CIL tank.

Heap/Dump Leach Process. This is an alternative leaching process for relatively low-grade gold-bearing ores. The ore is placed onto pads with the addition of lime (to control pH) and sprayed with weak cyanide solution. The solution slowly infiltrates through the heap to dissolve the gold into solution. Heaps are lined to prevent loss of the solution. The ore may either be crushed or uncrushed, and the leaching process continues for several weeks or months. The dissolved gold collects in drains at the edges of the heap and is pumped to a gold recovery circuit.

Elution. The washing of loaded carbon in hot water, caustic and cyanide solution to remove gold to the washing liquor. The resulting liquor is known as a pregnant solution. Acid is used prior to elution to remove inorganics.

Electrowinning. The application of a current to the pregnant solution to precipitate gold onto steel wool cathodes. Excess steel wool may be dissolved in hydrochloric acid to leave crude gold.

Smelting. The melting of crude gold separates impurities that float to the surface as slag. The slag is poured off and the molten gold is poured into moulds. The resulting mine bars (or gold doré) contain some silver and base metals.

Refining: Refining is the production of gold ingots from doré, and is carried out at a limited number of sites (eg. the Perth Mint). The Perth Mint refining process involves melting of the gold doré and injecting with chlorine gas under high pressure. Silver and base metals form gaseous chloride compounds, which are ducted via an extractor system to a wet scrubber, where particulates are removed and residual chlorine is neutralised. When the gold melt has attained 99.9% purity it is cast as ingots. Refining is not covered in this manual.

3.0 Likely Emissions

Estimates of emissions of listed substances to air, water and land shall be reported for each substance that exceeds a defined threshold value of 'usage' or emission. The reporting list and detailed information on thresholds are contained in *The NPI Guide*.

It is the responsibility of gold ore processing facilities to determine which NPI substances are triggered for reporting. Table 1 indicates those NPI substances likely to be of relevance where the threshold may be triggered by the gold ore processing industry, and the most appropriate method of determining whether the threshold is triggered. This table is intended as a guide to substances that may need to be reported for gold ore processing facilities.

Table 1 - NPI-Listed Substances Likely to Trigger Reporting Thresholds, and Proposed Methods for Determining Emissions

SUBSTANCE	TRIGGER	METHOD **
Acetone	Usage	INV
Ammonia (total)	Usage (Coincidental production)	INV, E/C
Antimony & compounds	Usage (Ore content)	D/M, G/F
Arsenic & compounds*	Usage (Ore content)	D/M, G/F
	and/or fuel/power usage	C
Beryllium & compounds	Usage (Ore content)	D/M, G/F
	and/or fuel/power usage	C
Boron & compounds	Usage (Ore content)	D/M, G/F
Cadmium & compounds*	Usage (Ore content)	D/M, G/F
	and/or fuel/power usage	C
Carbon disulfide	Usage (Coincidental production)	E/C
Carbon monoxide*	Fuel use	INV
Chromium (III) compounds	Usage (Ore content)	D/M, G/F
	and/or fuel use	INV
Chromium (VI) compounds*	Usage (Ore content)	D/M, G/F
	and/or fuel use	INV
Cobalt & compounds*	Usage (Ore content)	D/M, G/F
Copper & compounds	Usage (Ore content)	D/M, G/F
	and/or fuel/power usage	C
Cyanide (inorganic) compounds*	Usage	INV
Fluoride compounds*	Usage (Ore content)	D/M, G/F
	and/or fuel use	INV
Hydrochloric acid	Usage	INV
	and/or fuel use	INV
Hydrogen sulfide	Usage	INV
Lead & compounds*	Usage (Ore content)	D/M, G/F
	and/or fuel/power usage	C
Magnesium oxide fume	Fuel/power usage	C
Manganese & compounds	Usage (Ore content)	D/M, G/F
Mercury & compounds*	Usage (Ore content)	D/M, G/F
	and/or fuel/power usage	C

Table 1 - NPI-Listed Substances Likely to Trigger Reporting Thresholds, and Proposed Methods for Determining Emissions cont’.

SUBSTANCE	TRIGGER	METHOD *
Methyl ethyl ketone	Usage	INV
Nickel & compounds	Usage (Ore content)	D/M, G/F
	and/or fuel/power usage	C
Nickel carbonyl*	Fuel/power usage	C
Nickel subsulfide*	Fuel/power usage	C
Oxides of Nitrogen*	Fuel usage	INV
Particulate Matter 10.0 um*	Fuel usage	INV
Polychlorinated dioxins and furans	Fuel/power usage	INV, C
Polycyclic aromatic hydrocarbons (PAHs)*	Fuel usage	INV
Selenium & compounds	Usage (Ore content)	D/M, G/F
Sulfur dioxide*	Usage (Coincidental production)	E/C
	and/or fuel use	INV
Sulfuric acid*	Usage (Coincidental production)	E/C
Total Nitrogen*	Discharge to surface waters (sewage plants)	D/M, E/F
Total Phosphorus*	Discharge to surface waters (sewage plants)	D/M, E/F
Total Volatile Organic Compounds (VOC)	Fuel usage or design bulk storage	INV, C
Zinc and compounds	Usage (Ore content)	D/M, G/F

* Substances listed in Table 1 of *The NPI Guide*.

** A number of methods may be used to determine emissions of NPI substances. The method used will be related to the substance category and available information:

- D/M : Direct Measurement - direct measurement of emissions stream (total N and P) or characterisation of the ore body.
- INV: Inventory - inventory of material usage (chemicals, fuel), with NPI content of materials identified.
- G/F : Generic Factor - generic factor applies to default concentrations to be used in the absence of facility-specific data.
- E/F : Emission Factor - emission factor to determine content in discharge stream (total N and P).
- C : Capacity - capacity applies to the storage capacity of a facility, maximum combustion rate, consumption of energy or potential maximum power consumption.
- E/C : Engineering Calculation - engineering calculations may be used for a number of substances such as sulfur dioxide.

The NPI Guide, along with Worksheets 1 and 2 (at the front of this Handbook), are designed to assist facilities in determining substances that exceed reporting triggers.

You should note that while the reporting threshold for a substance may not be triggered during one reporting period, it may be triggered in another reporting period. As such, it is important to review NPI reporting requirements each reporting period.

3.1 Reporting Thresholds

Thresholds have been set for five categories, although a substance may exceed thresholds in more than one category (eg. copper may trigger reporting through its use and/or the facility's fuel usage). These are detailed below in simple terms. The NPI reporting list and detailed information on thresholds are contained in *The NPI Guide*.

3.1.1 Category 1

Category 1 substances trigger reporting through the 'use' of 10 tonnes or more per year of that substance.

Use has a very broad definition within the NPI and includes coincidental production and handling. Within the gold industry trace metals within ore may trigger reporting thresholds, as may the coincidental production of carbon disulfide from the breakdown of xanthates.

Ore handled at gold ore processing facilities may contain a sufficient concentration of NPI metals & compounds to trigger the Category 1 reporting threshold of 10 tonnes per annum.

Ore will need to be characterised for all NPI metals & compounds to determine the contribution of ore metal 'use' to the total facility 'use' of metals and compounds.

Direct measurement by representative sampling is the most accurate means of characterising ore and hence determining 'usage' of trace metals as the metals content of ore will vary between and within facilities. In the absence of facility-specific assays, generic ore assays may be used as the basis for reporting of metals 'usage'. These generic assays are presented in Appendix A.

Where substances are 'used' as a result of coincidental production, such as carbon disulfide from the decay of xanthates, engineering calculations may be appropriate to determine the amount that is 'used' based on the chemical reaction rates.

Reference to facility inventories should allow the mass of added material 'used' to be determined.

3.1.2 Category 1a

This category considers total volatile organic compounds (VOCs) only and the threshold is triggered through either the mass of VOCs used annually or the total VOC storage capacity of the facility.

The reporting threshold for a category 1a substance is exceeded in a reporting period if the activities involve the use of 25 tonnes or more of the substance in that period. The reporting threshold for a category 1a substance is only exceeded for bulk storage facilities if their design capacity also exceeds 25 kilotonnes.

VOC emission estimation from tanks is addressed by the *EET Manual for Fuel and Organic Liquid Storage*.

3.1.3 Category 2a

Category 2a encompasses products of combustion.

Reporting thresholds are triggered if a facility:

-
- burns 400 tonnes or more of fuel or waste in a year; or
 - burns 1 tonne or more of fuel or waste in an hour at any time during the reporting year.

Exceedence of threshold triggers may be determined through reference to masses of fuel used from facility inventories, or maximum fuel combustion rates.

3.1.4 Category 2b

Category 2b encompasses products of combustion.

Reporting thresholds are triggered where a facility:

- burns 2,000 tonnes or more of fuel or waste in a year;
- consumes 60,000 megawatt hours or more of energy in a year; or
- the maximum potential power consumption of the facility at any time in the year is rated at 20 megawatts or more.

3.1.5 Category 3

Category 3 substances are nitrogen and phosphorus. These are reportable if emissions to water (excluding groundwater) exceed the following scheduled amounts:

- 15 tonnes per year of total nitrogen
- 3 tonnes per year of total phosphorus

Direct measurement (through representative sampling) of the total nitrogen and phosphorus content of surface water discharges is likely to be the most appropriate means of determining whether reporting thresholds are triggered.

4.0 Emission Estimation

Estimates of emissions of NPI-listed substances to air, water and land should be reported for each substance that triggers a threshold. The reporting list and detailed information on thresholds are contained in *The NPI Guide* at the front of this Handbook.

In general, there are four types of emission estimation techniques (EETs) that may be used to estimate emissions from your facility.

The four types described in *The NPI Guide* are:

- sampling or direct measurement;
- mass balance;
- fuel analysis or other engineering calculations; and
- emission factors.

Select the EET, (or mix of EETs), that is most appropriate for your purposes. For example, you might choose to use a mass balance to best estimate fugitive losses from pumps and vents, direct measurement for stack and pipe emissions, and emission factors when estimating losses from storage tanks and stockpiles.

If you estimate your emission by using any of these EETs, your data will be displayed on the NPI database as being of ‘acceptable reliability’. Similarly, if your relevant environmental authority has approved the use of EETs that are not outlined in this handbook, your data will also be displayed as being of ‘acceptable reliability’.

This Manual seeks to provide the most effective emission estimation techniques for the NPI substances relevant to this industry. However, the absence of an EET for a substance in this handbook does not necessarily imply that an emission should not be reported to the NPI. The obligation to report on all relevant emissions remains if reporting thresholds have been exceeded.

You are able to use emission estimation techniques that are not outlined in this document. You must, however, seek the consent of your relevant environmental authority. For example, if your company has developed site-specific emission factors, you may use these if approved by your relevant environmental authority.

You should note that the EETs presented in this manual relate principally to average process emissions. Emissions resulting from non-routine events are rarely discussed in the literature, and there is a general lack of EETs for such events. However, it is important to recognise that emissions resulting from significant operating excursions and/or accidental situations (eg. spills) will also need to be estimated. Emissions to land, air and water from spills must be estimated and added to process emissions when calculating total emissions for reporting purposes. The emission resulting from a spill is the net emission, ie. the quantity of the NPI reportable substance spilled, less the quantity recovered or consumed during clean up operations.

Those techniques available for estimating emissions of NPI substances from gold ore processing activities are detailed in Table 2.

The estimation techniques detailed provide a range of options for facilities. These EETs may be supplemented by other techniques to develop facility-specific EETs or to confirm the accuracy of alternate EETs.

While particular estimation methods are generally more suited to some applications, the estimation method selected will be dependent upon a number of factors, such as:

- cost of estimation techniques;
- ease of measurement or monitoring;
- availability of suitable emission factors;
- level of accuracy desired;
- nature of the substance; and
- existing monitoring and data availability.

It should be appreciated that for reportable substances (eg. cyanide and metals), the emission of all compounds of the substance must be reported.

The NPI addresses the total loading, of those forms of a substance required by the NPI, to the environment and while the emission estimation takes account of both bioavailable and non-bioavailable forms of a substance (except for total nitrogen and phosphorus emissions) they are not distinguished in reported data. For example the NPI requires that inorganic cyanide compounds only are reported. The form in which cyanide is emitted should be factored into emissions estimation where practicable, although this may be very difficult to achieve where extensive cyanide complexes are emitted. Where this is the case **total cyanide** emissions should be reported.

In reporting emissions it is important to note that while the reporting threshold for a substance may be triggered this does not mean that the emissions will be significant. For example most trace metals in the processed ore are likely to be disposed of to the TSFs. However only emissions from TSFs must be reported within the NPI process.

The NPI has a commitment of not requiring any additional monitoring by facilities in order to estimate their emissions. While monitoring is an EET available to facilities, a range of EETs that do not require direct monitoring is available. However, in the absence of monitoring data, a lower level of accuracy can be expected.

Appendix B details sources of data that may already be available to facilities. This data may be used to assist in NPI reporting requirements.

A combination of these methods may be employed to estimate emissions to the environment from particular process areas, such as emissions from TSFs.

The *NPI Guide* provides guidance on the most appropriate approach to the estimation of emissions for particular categories of substances.

Table 2 - Relevant NPI-Listed Substances for the Gold Ore Processing Industry, and Recommended EETs

SUBSTANCE	PROCESSING			POWER GENERATION	SMELTING	TSFs	ROASTER	SEWAGE
	COMMINATION	FLOTATION, THICKENING, CYANIDATION, CARBON LOADING & ELUTION	CARBON REGENERATION KILNS					
D/M : Direct Measurement , M/B : Mass Balance , E/F : Emission Factors , E/C : Engineering Calculations , M : Modelling A : Emission to Air , W : Emission to Water , L : Emissions to Land, including Groundwater								
Acetone		A M/B						
Ammonia (total)		A D/M , M/B , E/C						
Antimony & compounds	A M/B				A M/B	W,L M/B	A M/B	
Arsenic & compounds	A M/B			A E/F	A M/B	W,L M/B	A M/B	
Beryllium & compounds	A M/B			A E/F	A M/B	W,L M/B	A M/B	
Boron & compounds	A M/B				A M/B	W,L M/B	A M/B	
Cadmium & compounds	A M/B			A E/F	A M/B	W,L M/B	A M/B	
Carbon disulfide		A D/M , M/B , E/C	A D/M , M/B , E/C					
Carbon monoxide			A D/M	A E/F				
Chromium (III) compounds	A M/B			A E/F	A M/B	W,L M/B	A M/B	
Chromium (VI) compounds	A M/B			A E/F	A M/B	W,L M/B	A M/B	
Cobalt & compounds	A M/B				A M/B	W,L M/B	A M/B	
Copper & compounds	A M/B			A E/F	A M/B	W,L M/B	A M/B	

Table 2 - Relevant NPI-Listed Substances for the Gold Ore Processing Industry, and Recommended EETs cont'

SUBSTANCE	PROCESSING			POWER GENERATION	SMELTING	TSFS	ROASTER	SEWAGE
	COMMINUTION	FLOTATION, THICKENING, CYANIDATION, CARBON LOADING & ELUTION	CARBON REGENERATION KILNS					
D/M : Direct Measurement , M/B : Mass Balance , E/F : Emission Factors , E/C : Engineering Calculations , M : Modelling A : Emission to Air , W : Emission to Water , L : Emissions to Land, including Groundwater								
Cyanide (inorganic) compounds		A D/M , M/B , M , E/F	A D/M , M/B , M , E/F		A D/M , M/B , M , E/F	A , W , L D/M , M/B , M , E/F	A D/M , M/B , M , E/F	
Fluoride compounds	A M/B			A E/F	A M/B	W , L M/B	A M/B	
Hydrochloric acid		A D/M , M/B		A E/F				
Hydrogen sulfide			A D/M , M/B					
Lead & compounds	A M/B			A E/F	A M/B	W , L M/B	A M/B	
Magnesium oxide fume				A E/F	A E/F		A E/F	
Manganese & compounds	A M/B				A M/B	W , L M/B	A M/B	
Mercury & compounds	A M/B			A E/F	A M/B	W , L M/B	A M/B	
Nickel & compounds	A M/B			A E/F	A M/B	W , L D/M , M/B	A D/M , M/B	
Nickel carbonyl				A E/	C			
Nickel subsulfide				A E/F				
Oxides of Nitrogen			A E/F	A E/F				

Table 2 - Relevant NPI-Listed Substances for the Gold Ore Processing Industry, and Recommended EETs cont'

SUBSTANCE	PROCESSING			POWER GENERATION	SMELTING	TSFS	ROASTER	SEWAGE
	COMMINUTION	FLOTATION, THICKENING, CYANIDATION, CARBON LOADING & ELUTION	CARBON REGENERATION KILNS					
D/M : Direct Measurement , M/B : Mass Balance , E/F : Emission Factors , E/C : Engineering Calculations , M : Modelling A : Emission to Air , W : Emission to Water , L : Emissions to Land, including Groundwater								
Particulate Matter ≤10.0 um (PM ₁₀)	A D/M , E/F , M	A D/M , E/F , M	A D/M , E/F , M	A D/M , E/F , M	A D/M , E/F , M	A D/M , E/F , M	A D/M , E/F , M	
Polychlorinated dioxins and furans				A E/F				
Polycyclic aromatic hydrocarbons				A E/F				
Selenium & compounds	A M/B				A M/B	W , L M/B	A M/B	
Sulfur dioxide			A E/F	A E/F	A D/M , M/B		A D/M , M/B	
Sulfuric acid				A D/M , M/B, E/C	A D/M , M/B, E/C		A D/M , M/B, E/C	
Total Nitrogen								W E/F , D/M
Total Phosphorus								W E/F , D/M
Total Volatile Organic Compounds		A E/F , E/C			A E/F , E/C		A E/F , E/C	
Zinc and compounds	A M/B				A M/B	W , L M/B	A M/B	

4.1 Elements of the Environment

4.1.1 Emissions to Air

Significant emissions to air within the gold ore processing industry will be related to:

- stack emissions from roasters and smelters;
- the stockpiling, movement and comminution of ore;
- the operation of process plants such as CIP and CIL circuits, and heap leaches; and
- the operation of tailing storage facilities (TSFs).

Emissions to air are estimated from their point of creation rather than at the facility boundary. Emissions estimation takes no account of the fate of emitted substances, such as the speed of their subsequent decay within the atmosphere.

Air emissions may be categorised as:

Fugitive emissions

These are emissions that are not released through a vent or stack. Examples of fugitive emissions include dust from stockpiles, volatilisation of vapour from vats or open vessels, and material handling. Emissions emanating from ridgeline roof-vents, louvres, and open doors of a building as well as equipment leaks, and leaks from valves and flanges are also examples of fugitive emissions.

Emission factor EETs are the usual method for determining losses through fugitive emissions.

Point source emissions

These emissions are exhausted into a vent or stack and emitted through a single point source into the atmosphere. An air emissions control device such as a carbon adsorption unit, scrubber, baghouse, or afterburner may 'treat' stack emissions prior to their release, reducing their total loading to the atmosphere.

4.1.2 Emissions to Water

Emissions of substances to water can be categorised as discharges to:

- Surface waters (eg. lakes, rivers, dams, and estuaries);
- Coastal or marine waters; and
- Stormwater.

Groundwater is not considered as a 'water body' within the context of NPI reporting. Groundwater is included within emissions to land.

Significant emissions to water within the gold ore processing industry will be related to:

- runoff and erosion from the facility area (refer to the *EET Manual for Mining*);
- the discharge of treated process waters (eg. treated TSF decant water) to surface waters;
- the discharge of sewage and domestic wastewaters to surface waters; and
- spills to surface waters.

The most accurate techniques for estimating emissions to the environment via wastewater is likely to be direct measurement. However, facilities may use other EETs for the purposes of reporting within the NPI.

4.1.3 Emissions to Land

Emissions of substances to land on-site may include solid wastes, slurries, sediments, spills and leaks, storage and distribution of liquids, and the use of chemicals to control various elements of the environment where these emissions contain listed substances. These emission sources can be broadly categorised as:

- surface impoundments of liquids and slurries, except for purpose built TSFs, solid waste dumps and waste rock dumps; and
- unintentional leaks and spills.

Discharges to land such as purpose built TSFs, solid waste dumps and waste rock dumps are classed as transfers. Emissions from these facilities to the environment are, however, included within the scope of the NPI and will generally be addressed as either emissions to groundwater (land) or to air.

5.0 Mass Balance

Mass balance provides an estimate of emissions where known quantities of substances are supplied to a process, and the process fate of the substance is both known and quantifiable.

It is essential that the mass balance calculation addresses all losses and fates of a substance and utilises the best available data.

As a result of inherent errors in the estimation of inputs to and losses from a facility or process, and the fates of those substances, the effectiveness of a mass balance approach in estimating minor emissions may be questionable and may contain broad error bands.

5.1 Water Balance

Tailings Storage Facilities (TSFs) represent a significant potential emission source of some NPI substances. A comprehensive water balance will assist in the identification and quantification of emission pathways, allowing the emission pathways of soluble and volatile substances to be more accurately identified and estimated (BPEMIM, Cyanide Management, 1995).

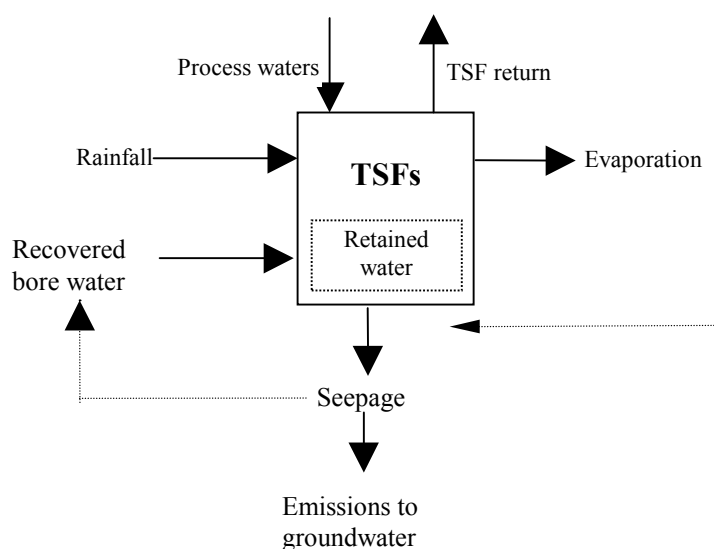


Figure 4 - TSF Water Balance

A comprehensive water balance, when used in conjunction with EETs, will facilitate the estimation of emissions of soluble NPI substances (eg. metals) from TSFs.

For example, the difference between known water inputs and losses (including rainfall and evaporation) in the water balance can normally be assumed to represent seepage. Emissions of soluble NPI substances may be estimated through direct measurement of monitored boreholes and relating this data to the known hydraulic conductivity of the soils.

It is noted, however, that estimates of the inputs/outputs of some water balances may have significant associated error bands. Work recently undertaken by MERIWA (MERIWA Project M241, 1998) demonstrates the errors that may be associated with the calculation of evaporative

losses from the surface of TSFs. This is well illustrated by the following example from MERIWA Project Report M241, 1998;

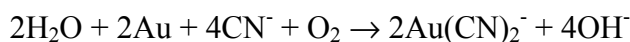
For a TSF of 100 ha, an evaporative loss of 100 mm is equivalent to a total volume of 100,000m³.

Evaporative losses are influenced by a wide variety of factors. Salinity may reduce evaporation by as much as 60 - 95% of the potential evaporative rate. As such estimating to an accuracy of 100 mm may require extensive study and characterisation and any errors in calculating these losses may result in significant inaccuracies.

5.2 Cyanide Balance

The NPI requires that inorganic cyanide compounds be reported where the threshold is triggered. As such in the gold ore processing industry 'total cyanide' emissions should be reported.

Cyanide is used in the leach stage of gold ore processing, and is typically added at a rate of 0.5kg NaCN per tonne of ore. The cyanide bonds with gold to form a $2\text{Au}(\text{CN})_2^-$ complex (as shown below) allowing the gold to be extracted through adsorption onto activated carbon granules or cementation with zinc powder. Lime is used to buffer the slurry pH to optimise cyanide in solution levels and minimise the formation of HCN gas.



When used in the gold process cyanide may:

- be carried through the system in a dissolved form to be reused in recycle circuits or through TSF return waters;
- seep from TSFs as a ground emission;
- convert to different cyanide states such as thiocyanate and cyanate;
- complex with metals such as copper, iron and cobalt;
- decompose to form ammonia and bicarbonate; and
- be released in gaseous form as hydrogen cyanide (HCN).

The behaviour of cyanide within TSFs is extremely complex and has not been accurately modelled to date. Current research projects (such as AMIRA P497a) are being conducted to address this lack of knowledge.

Within the TSFs structure, evaporation, reduction, oxidation, precipitation, adsorption, desorption, exchange reactions are just a few of many possible simultaneous events.

The kinetics of all these reactions are influenced by the general chemistry/geochemistry. This includes variations in:

- pH;
- electrochemical potential (Eh);
- salinity;
- temperature;
- density of solids;
- type of minerals;
- the individual metal cyanide complexes and their concentration; and
- the presence of any free cyanide and its derivative.

While it is accepted that most conventional TSFs facilities seep to some extent (it is only the degree of seepage that varies between structures) into the underlying formations or groundwater, the transport out of the TSF of cyanide compounds can not currently be assumed or calculated due to the above still unresolved complexity. Research data in one case has shown that, despite seepage to groundwater, no cyanide compounds have moved out of a TSF. In another case where seepage rates were similar, significant contamination of groundwater occurred. While total cyanide discharges to the respective TSFs were similar, the cyanide speciation, mineralogy and timing of the TSF of the two sites differed. (Source: Roger Schulz, 1998)

The fate of cyanide within the ore processing stage is relatively complex and cyanide (for the purposes of NPI reporting) may be released to the environment through a number of pathways including:

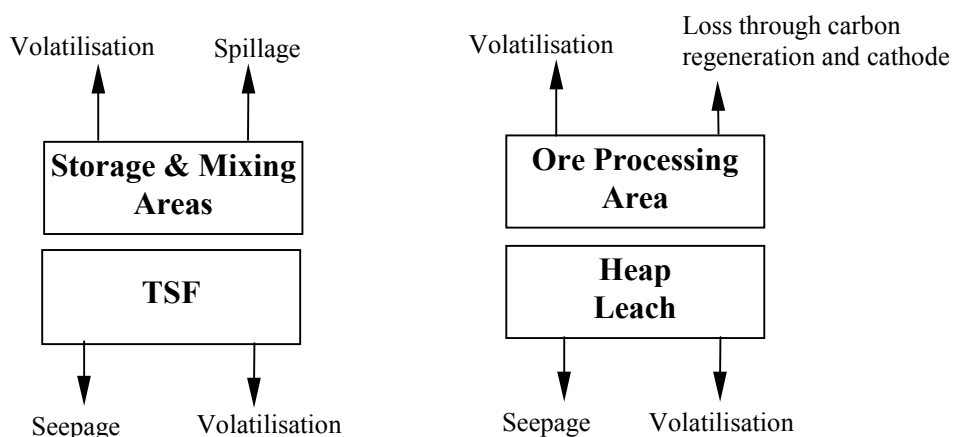


Figure 5 - Cyanide Balance

Regardless, all cyanide is either ultimately emitted to the environment, decomposed or complexed within the TSFs.

When estimating emissions of cyanide to the environment it is important that **total cyanide** is reported. Therefore emissions of HCN should be converted to CN⁻ for reporting purposes. Section 9.4 discusses this in more detail.

As a result of losses both within and from the process, cyanide is usually the most expensive reagent cost at a facility. For this reason, in addition to the environmental, health and safety considerations, cyanide fates within the ore processing industry have been extensively studied.

A mass balance approach may be employed to develop a flow diagram of cyanide additions and losses to the process. However, it is likely that the mass balance approach will be supported by other EETs, such as direct measurement and modelling, in order to increase the accuracy of estimated emissions.

The accuracy of the mass balance approach may be greatly enhanced by the development of a cyanide management plan, regular cyanide audits and the implementation of an environmental monitoring program, such as proposed in the 'Cyanide Management' booklet from the Best Practice Environmental Management in Mining series (1998).

Cyanide mass balance is addressed below for the separate parts of the ore processing sequence.

5.2.1 Cyanide Emissions from Storage and Mixing Areas

Cyanide emissions from storage and mixing areas may be mainly due to spillage losses and may be estimated through effective record keeping of all spills and inventories of supplies.

Losses to ground and water may be differentiated through effective record keeping of all spills, and the fate of spilled material (washed to treatment process, absorbed and disposed of to licensed site etc).

These emissions shall be reported as CN⁻ equivalent masses.

5.2.2 Cyanide Emissions from the Ore Processing Area (Leaching, Flotation & Smelting)

For the mass balance presented above it may be assumed that:

- Cyanide addition rates are known;
- Cyanide carry through concentrations are known;
- Cyanide TSF return water concentrations are known ; and
- Cyanide volatilisation masses from leaching tanks are estimated as 1% of the total cyanide addition rate where facility-specific data is not available [Heath et al, 1998] (see Section 6.2.1)

Thus the mass balance approach may be used to estimate the emissions of cyanide through the regeneration of activated carbon and loss at the cathode during smelting.

Cyanide losses will occur in the carbon regeneration, elution and electrowinning areas. While this cyanide rapidly degrades to form ammonia the original emission form is as HCN and as such is reported as a cyanide emission. No attempt is made to differentiate between the masses emitted from these areas due to the difficulties inherent in their individual estimation.

$$\text{Mass of cyanide lost during regeneration of carbon and at cathode during smelting (kg)} = \left[\text{Mass of cyanide added to process (kg)} + \text{Mass of cyanide in TSF return water (kg)} \right] - \text{Mass of cyanide carried to TSF (kg)} - \text{Mass of cyanide lost through Volatilisation}^1 \text{ (kg)}$$

¹ Assume 1% if specific data is not available.

5.2.3 Cyanide Emissions from TSFs

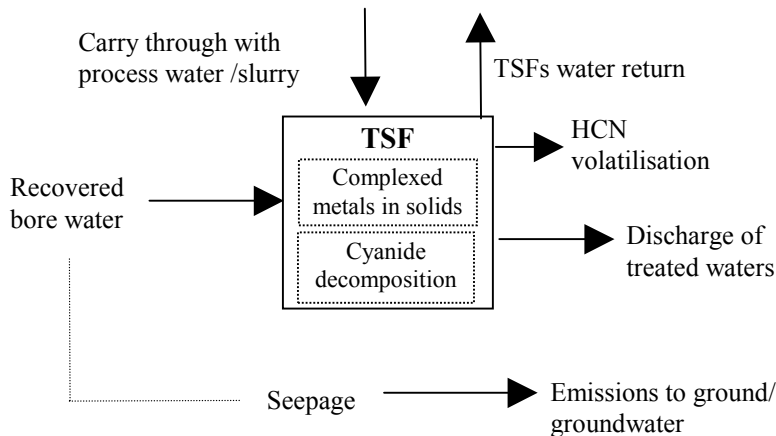


Figure 6 - Mass Balance of Cyanide Emissions from TSFs

The potential for contamination of ground and/or groundwater resources may be a significant environmental risk for the gold ore processing facilities. Seepage from TSFs may be the most likely source of groundwater contaminants within facilities. Industry and regulators have recognised this potential risk and many facilities have seepage control and groundwater monitoring and management systems in place.

These systems include:

- under drainage of TSFs;
- interception trenches and drains;
- groundwater recovery bores;
- groundwater monitoring bores; and
- cyanide destruction technologies.

The total mass of cyanide lost within the tailings circuit (ie. complexed with tailings solids, decomposed or emitted to the air or ground) may be estimated using the equation:

$$\begin{array}{rcl} \text{Mass of cyanide} & = & \text{mass of cyanide} & - & \text{mass of cyanide in} \\ \text{lost to TSFs} & & \text{carried to TSF} & & \text{TSF return water} \\ \text{(kg)} & & \text{(kg)} & & \text{(kg)} \end{array}$$

Cyanide may be emitted to the environment via the following pathways:

Seepage

It is generally accepted that all TSFs are not impermeable and some seepage will occur, (BPEMIM, Cyanide Management). However, seepage rates will vary considerably between TSFs based on their methods of construction and management regimes. The rate of water movement through underlying soils will again be very site-specific.

The mass of cyanide lost to the environment through groundwater seepage may be estimated using:

- seepage rates; and
- the concentration of total cyanide in TSFs return water.

While these seepage rates will be facility-specific, generic seepage rates of between **0 - 10 %** have been quoted within the industry (Mt Keith Nickel 1996, ANCOLD per. comms.). The 10% figure can be used as a point of reference for reporting purposes.

Individual facilities will need to determine the percentage rate of seepage, which is applicable to their facility as a whole, or individual TSFs within the facility, and apply this percentage to the mass balance calculation of seepage losses.

It may be appropriate to use a number of EETs to determine losses.

Cyanide concentrations in seepage may be assumed as being equal to that in the TSFs return water (total cyanide) unless facility-specific data suggests otherwise.

$$M = [V * S] * C / 100$$

where

M	=	mass of cyanide emitted through seepage, kg
V	=	volume of water and/or slurry to TSF, m ³
S	=	seepage rate, %
C	=	concentration of cyanide, kg/m ³

In the absence of facility-specific data the following parameters may be used in calculating seepage;

- 10 % seepage rate;
- total cyanide concentrations equal to that in TSFs return water; and
- no bore water recovery

Borehole recovery may be factored into the estimation technique where cyanide concentration, and volumes of recovered bore water are known.

Where seepage rates of less than 10% are used these should be justified.

Volatilisation

In natural degradation most 'free' cyanide is lost through volatilisation (BPEMIM, Cyanide Management, 1998). The cyanide is volatilised as HCN, which ultimately breaks down to form ammonia and carbon dioxide

Volatilisation is enhanced by low pH (acidic) conditions. These conditions will be present in some TSFs storage facilities where the large surface area encourages acidification through increased contact with atmospheric carbon dioxide [BPEMIM, 1998].

At present, there is no reliable method for estimating emissions of cyanide from TSFs using a mass balance. The emissions factors for volatilisation from TSFs presented in Section 6.2.2 may be used to estimate these emissions.

Overflow

Cyanide, and other NPI substances, may be emitted to the environment as a result of TSF overflow. In these circumstances the mass of cyanide emitted may be estimated by multiplying the volume of material lost by the concentration of cyanide in the tailings material.

5.2.4 Cyanide Emissions from Heap/Dump Leaches

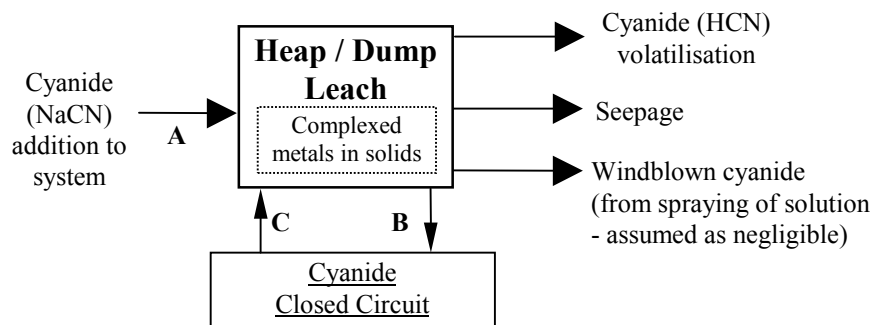


Figure 7 - Mass Balance of Cyanide from Heap/Dump Leaches

The masses of cyanide added to the system will be known through monitoring of streams A, B and C. Based on this data the mass of cyanide loss within and from the leach system may be assumed to be equal to the masses in stream A. This assumes that a constant cyanide concentration is maintained within the leach process.

This mass of cyanide may be both bound up within the leach system and emitted to the environment via a number of pathways.

Seepage

Seepage from the heap/dump leach pads may be estimated using the equation below:

$$\text{mass of cyanide emitted through seepage (kg)} = \left[\text{volume of water supplied to heap leach (m}^3\text{)} - \text{volume of water intercepted}^1 \text{ (m}^3\text{)} \right] * \text{concentration of cyanide added to heap leach (kg / m}^3\text{)}$$

¹ Refers to volume intercepted in cut off trench or other seepage recovery mechanism

Volatilisation

Volatilisation would normally be expected to be the most significant cyanide emission pathway from dump/heap leach facilities.

At present, there is no reliable method for estimating emissions of cyanide from leach systems using a mass balance calculation, because volatilisation of cyanide cannot be distinguished from other fates such as natural decomposition.

It is proposed that the mass of cyanide lost to the environment, through volatilisation and other fates, is assumed to be HCN emissions to air. In this way a standard stoichiometry may be applied to these losses.

Cyanide bound to gold (and other recovered metals) and retained in the ore should be included within the mass balance where known.

$$\begin{array}{r} \text{Mass of cyanide} \\ \text{lost through} \\ \text{volatilisation} \\ \text{(and other fates)} \\ \text{(kg)} \end{array} = \begin{array}{r} \text{Mass of} \\ \text{cyanide added} \\ \text{to leach} \\ \text{system} \\ \text{(kg)} \end{array} - \left[\begin{array}{r} \text{Mass of cyanide} \\ \text{emitted to the} \\ \text{environment} \\ \text{through seepage} \\ \text{(kg)} \end{array} + \begin{array}{r} \text{Mass of cyanide lost} \\ \text{through complexing} \\ \text{with recovered gold} \\ \text{(and other metals)} \\ \text{(kg)} \end{array} \right]$$

*Alternative cyanide EETs include Emission Factors,
Modelling & Direct Measurement*

5.3 Metals

Metals may be emitted:

- through seepage from TSFs and heap/dump leach pads;
- as dust; and
- as a result of TSF overflow.

The mass balance approach may be utilised to estimate emissions of metals in a manner similar to that used to estimate the emission of cyanide through seepage.

The mass of reportable NPI metals lost to the environment through seepage may be estimated using:

- estimates of seepage rate; and
- the concentration of NPI metals in TSFs return water or dump/heap leach liquors

While these seepage rates will be facility-specific, generic seepage rates of between **0 - 10 %** has been quoted within the industry (Mt Keith Nickel 1996, ANCOLD, per. comms.).

Metals concentrations should be assumed as being equal to that in the **TSFs return water** unless facility-specific data suggests otherwise.

$$M = [V * S] * C_m / 100$$

where

- M = mass of metal emitted through seepage, kg
- V = volume of water and/or slurry to TSF, m³
- C_m = concentration of metal, kg/m³

In the absence of facility-specific data the following data should be used in calculating seepage:

- 10 % seepage rate;
- metals concentration equal to that in TSFs return water; and
- no bore water recovery.

Borehole recovery may be factored into the estimation technique where metal concentrations and volumes of recovered bore water are known.

$$\begin{array}{r} \text{Mass of metal} \\ \text{emitted through} \\ \text{seepage with bore} \\ \text{recovery} \\ \text{(kg)} \end{array} = \begin{array}{r} \text{Mass of metal} \\ \text{emitted through} \\ \text{seepage} \\ \text{(kg)} \end{array} - \left[\begin{array}{r} \text{Concentration *} \\ \text{of metal in} \\ \text{recovered} \\ \text{bore water} \\ \text{(kg / m}^3\text{)} \end{array} * \begin{array}{r} \text{Volume} \\ \text{of recovered} \\ \text{bore water} \\ \text{(m}^3\text{)} \end{array} \right]$$

Alternative metals EETs include Direct Measurement & Modelling

5.4 Chemical Usage

The emission of chemicals from facilities from some sources (either as a result of normal operations, spillages or incidents) may be estimated through mass balance.

Process and domestic chemicals used within the facility may be emitted to the environment. The full inventory of these chemicals used within a reporting period, may be assumed either to be emitted to the environment or transferred to an alternative disposal, recycling or reuse facility.

In order to estimate the fate of chemicals, and their component NPI substances, the following approach should be taken:

- Mass of NPI substances within chemicals determined (including coincidental production)
- Inventory (or hazardous substances registers) of chemical usage maintained
- Fate of chemical determined -
 - ⇒ is chemical emitted to the environment or transferred?
 - ⇒ is chemical treated prior to emission from the facility?
 - ⇒ is chemical emitted to air, water or land?
 - ⇒ does chemical undergo partitioning into other forms?
 - ⇒ what are the fates of partitioned substances?

This approach may be applied to chemical usage in areas such as:

- chemical storage areas;
- laboratories;
- workshops;
- kitchens;
- domestic; and
- washdown areas.

Alternative chemicals usage EETs include Direct Measurement

5.5 Roaster and Smelter Emissions

Emissions (eg. sulfur dioxide and metals) from roaster and smelter operations may be estimated through the use of mass balance. Some direct sampling may be desirable to improve components of the mass balance, eg. sulfur/metals content of process inputs and outputs. Some facilities may choose to estimate these emissions using only direct measurement and this may represent a more accurate EET.

It is important that the fates of component substances are considered within the mass balance and that all assumptions are stated. For example, it may be assumed that all sulfur is converted to sulfur dioxide during combustion, and ash content analyses may suggest that a percentage of some metals are emitted.

The mass balance approach allows fugitive and other emissions to the environment to be estimated.

5.5.1 Emissions Estimation for Roaster and Smelter operations

In a similar manner in which emissions from combustion are estimated, emissions from roaster and smelter operations may be estimated using a mass balance.

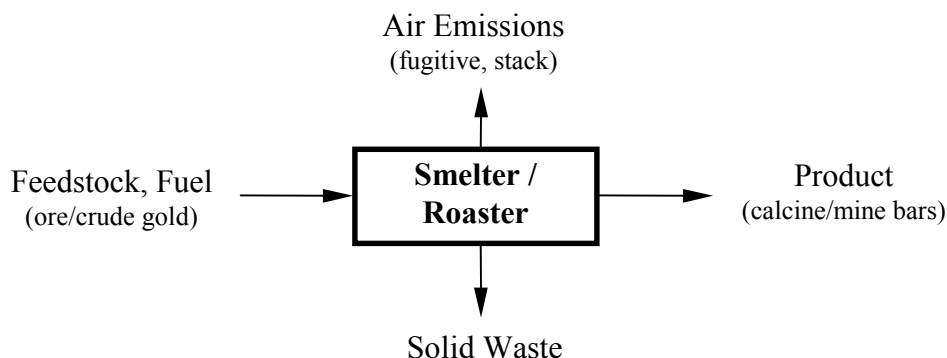


Figure 8 - Mass Balance for Smelter and Converter Operations

Air emissions may be estimated where substance concentration of the feedstock, fuel, product and solid wastes has been effectively characterised.

$$\text{Emission of substance (kg/hr)} = \text{Rate of Feedstock Addition (kg/hr)} * \frac{\text{wt \%}}{100} * \frac{\text{MW}_p}{\text{EW}_f}$$

where:

- wt % = weight percent of substance in feedstock.
- MW_p = molecular weight of substance emitted, kg/kg-mole
- EW_f = elemental weight of substance in feedstock, kg/kg-mole

Alternative roaster / smelter EETs include Direct Measurement

5.5.2 Emissions Estimation for Fuel

Fuel analysis can be used to predict SO₂, metals, and other emissions resulting from combustion.

The basic equation used in fuel analysis emission calculations is the following:

$$\text{Emission of Substance (kg/hr)} = \text{Rate of Fuel Usage (kg/hr)} * \frac{\text{wt \%}}{100} * \frac{\text{MW}_p}{\text{EW}_f}$$

where:

- wt % = weight percent of element in feedstock.
- MW_p = molecular weight of substance emitted, kg/kg-mole
- EW_f = elemental weight of substance in fuel, kg/kg-mole

SO₂ emissions from combustion can be calculated based on the concentration of sulfur in the fuel.

This approach assumes complete (100%) conversion of sulfur to SO₂. Therefore, for every kilogram of sulfur (EW = 32) burned, two kilograms of SO₂ (MW = 64) are emitted.

$$\text{Emission of SO}_2 \text{ (kg/hr)} = \text{Fuel Usage (kg/hr)} * \frac{\text{wt \% S}}{100} * \frac{\text{MW}_{\text{SO}_2}}{\text{EW}_S}$$

Where:

wt % S = weight percent of sulfur (as elemental S) in the fuel.

The emissions are estimated as kg/hr and as such should be multiplied by the hours of operation in order to determine the total emission load.

Guidance on emissions from fuel combustion may also be found in the following NPI EET Manuals:

- *Fossil Fuel Electric Power Generation EET Manual*;
- *Combustion Engines EET Manual*; and
- *Combustion in Boilers EET Manual*.

6.0 Emission Factors

An emission factor is a tool that is used to estimate emissions to the environment.

In this Manual, it relates the quantity of substances emitted from a source to some common activity associated with those emissions. Emission factors are obtained from US, European, and Australian sources and are usually expressed as the weight of a substance emitted.

Emission factors are used to estimate a facility's emissions by the general equation:

$$E_{kpy,i} = [A * \text{OpHrs}] * EF_i * [1 - (CE_i/100)]$$

where

- E_{kpy,i} = emission rate of pollutant i, kg/yr
- A = activity rate, t/hr
- OpHrs = operating hours, hr/yr
- EF_i = uncontrolled emission factor of pollutant i, kg/t
- CE_i = overall control efficiency for pollutant i, %.

Some emission factors may involve the use of more complex equations and require differentiation of substances fates. Estimation of cyanide fates is an example of a substance that may require the use of more complex EETs.

Emission factors are derived from direct measurement of actual emission loads from a range of similar plants or equipment. While emission factors have an empirical basis they are based on standard equipment and operating practices. As such, the site-specific characteristics of facilities will introduce inaccuracies to the use of emission factors, and with the increasing use of improved technologies and control methods; emission factors may become dated.

Emission factors may be verified at individual facilities by carrying out direct monitoring of emission sources and developing site-specific variations to the standard factors to reflect on-site operational processes and practices.

6.1 Carbon Disulfide

In the gold industry carbon disulfide is formed through the breakdown of xanthates which are added at the flotation stage of ore processing.

Xanthate breakdown is influenced by a number of factors. Within the gold ore processing industry the most significant of these factors are:

- pH (below pH 7 the xanthate decomposition rate increases dramatically)
- temperature (10°C rise in temperature may cause a threefold increase in decomposition rates)

[Source: WMC Report Ref 692 634, 1992]

The stoichiometry of xanthate decomposition, and hence CS₂ formation, will also vary according to the pH.

- Hydrolytic decomposition (alkali conditions) of the xanthate ion results in a stoichiometry of 1:0.5 (xanthate to CS₂).
- Hydrolysis decomposition (acidic conditions) of the xanthate ion results in a stoichiometry of 1:1 (xanthate to CS₂).

[Source: WMC Report Ref 692 634, 1992]

The decomposition stoichiometry will vary with the form of xanthate used at particular facilities. Facilities should verify the stoichiometry(s) to be applied based on their use of xanthate types.

The gold ore processing area will generally have an alkali pH (in order to minimise losses of cyanide as HCN). However at some facilities this may be very difficult to achieve.

TSFs are also likely to be alkali, although the geochemistry of the ore being handled may result in TSFs becoming acid.

Available data suggests a wide range of xanthate decomposition rates under varying conditions. Additionally, limited carry over of xanthate may take place with the product and some carry over to TSFs (approx. 2% [Society of Mining Engineers, 1976]) may also occur.

However, as the first point of reference, it can be assumed that 100% degradation of xanthate occurs within the processing area.

On this assumption CS₂ emission may be estimated using the equation:

Alkali Conditions (>7) :

$$\text{Emissions of CS}_2 \text{ (kg)} = \frac{0.5 * \text{Mass Xanthate (kg)} * \text{MW}_{\text{CS}_2}}{\text{MW}_{\text{xanthate}}}$$

Acidic Conditions (<7) :

$$\text{Emissions of CS}_2 \text{ (kg)} = \frac{1.0 * \text{Mass Xanthate (kg)} * \text{MW}_{\text{CS}_2}}{\text{MW}_{\text{xanthate}}}$$

Example 1 - Carbon Disulfide Emissions

A facility uses 150kg of Sodium Ethyl Xanthate (SEX), for each mole of SEX used, 0.5 moles of CS₂ are produced (alkali conditions).

Molecular Weight_{CS₂} (MW_{CS₂}) = 76g

Molecular Weight_{SEX} (MW_{SEX}) = 144g

$$\begin{aligned} \text{Emission of CS}_2 \text{ (kg)} &= 0.5 * \text{Mass Xanthate (kg)} * \text{MW}_{\text{CS}_2} / \text{MW}_{\text{xanthate}} \\ &= 0.5 * 150 * 76 / 144 \text{ kg} \\ &= 40 \text{ kg} \end{aligned}$$

Alternative CS₂ EETs include Direct Measurement

6.2 Cyanide

Extensive study has been carried out into the usage rates and fates of cyanide within the gold ore processing industry.

Cyanide fates within the gold process itself are also subject to a range of facility-specific factors including:

- ionic cyanide concentration;
- pH;
- tank geometry;
- aeration;
- agitation;
- wind velocity;
- salinity of process waters; and
- metals content of the ore.

The fates of cyanide will include:

- volatilisation;

- natural degradation;
- metal complexing;
- loss of dissolved fraction in seepage of TSFs water; and
- bound into TSFs solids.

As such the application of generic emission factors is not considered to be reliable in most situations.

6.2.1 Cyanide Emissions from the Ore Processing Area

Based on research carried out by CSIRO it is estimated that **1%** of total cyanide is lost through volatilisation as HCN within the processing area (Heath et al, 1998).

Alternatively, the emissions of HCN from individual process tanks within the CIP/CIL can be estimated using the equation:

$$E = ([0.013 * [HCN_{(aq)}] + 0.46] * A * T / 10^6) * 1000$$

Where:

E	=	Emission of HCN (kg)
[HCN _(aq)]	=	[NaCN] * 10 ^(9.2 - pH)
[NaCN]	=	Concentration (as mg/l) of NaCN in the leach/adsorption tank
pH	=	pH in the leach/adsorption tank
A	=	Surface area (m ²) of the leach/adsorption tank
T	=	Period of emissions (hours)

This approach:

- must be applied to each tank individually;
- should be calculated on a regular basis (as required to reflect changing tank conditions) or using mean values based on regular sampling of tank conditions; and
- is of unknown validity at HCN_(aq) concentrations below 60 mg/l.

Cyanide emissions should be reported as mass of CN rather than HCN and can be converted using the stoichiometry detailed below.

Mass of CN emitted (kg)	=	Mass of HCN (kg)	*	MW_{CN}/WM_{HCN}
Mass of CN emitted (kg)	=	Mass of HCN (kg)	*	0.96

6.2.2 Cyanide Emissions from the TSFs

Cyanide volatilisation from TSFs may be estimated from the surface area of the liquor within the TSFs using the emission factor:

$$\mathbf{1g \text{ of HCN per m}^2 \text{ per hour for each 100ppm of HCN}_{(aq)}}$$

(Ref: WMC, Pers. Comm. 1998)

However in order to apply this emission factor, the concentration of HCN_(aq) in the TSFs water must be known or estimated.

It has been estimated that volatilisation of HCN accounts for 90% of the natural degradation of cyanide from TSFs (Ellis, 1997; Simovic, 1984). However, volatilisation is extremely pH dependent as a result of the HCN/CN⁻ flux. A range of other factors also influences the rate of volatilisation although pH is the most significant factor.

This percentage degradation is however dependent on pH conditions. As such, where **'free'** **cyanide** concentration and pH of the TSF return water are known, the percentage degradation may be estimated based on the conditions detailed below;

Table 3 - Effect of pH on the Volatilisation of Cyanide

pH	Percentage of natural degradation due to volatilisation. (V%)
6	90 %
7	90 %
8	80 %
9	60 %
10	20 %
11	0 %
12	0 %

(Based on Ellis, 1997, Simovic, 1984)

This data is applied using the equation below:

$$\text{HCN volatilisation from TSFs (kg)} = \left[\text{Free cyanide concentration in TSF return water (kg / m}^3\text{)} * \text{Volume of water and/or slurry to TSF (m}^3\text{)} \right] * \text{V\% /100}$$

Alternative cyanide EETs include; Mass Balance, Modelling and Direct Measurement

6.3 Dust: PM₁₀ and Total Suspended Particulates (TSP)

Table 4 provides emission factors for PM₁₀ and TSP sources within the processing area. The PM₁₀/TSP ratio allows the PM₁₀ emission factor to be verified at the facility level where TSP monitoring is undertaken.

It should be noted that TSP is not a reporting requirement under the NPI and is used to estimate metals content of emitted dust only. Also, while PM₁₀ reporting is triggered by fuel usage all sources of PM₁₀ emissions must be estimated if the reporting threshold is triggered.

Emission factors for high and low moisture content ores are presented and are for uncontrolled emissions.

Metal emissions can be estimated as a fraction of the TSP emissions, based on available assay data. Where assay data and facility-specific information is not available for metals in dust emissions the concentrations in Appendix A should be used as a default to estimate metal emissions.

Dust emissions from TSFs should only be calculated from those TSFs with the potential to result in dust emissions.

With regards to emission controls for PM₁₀, in the absence of measured data, or knowledge of the collection efficiency for a particular piece of equipment, an efficiency of 90% should be used in the emission factor equation to calculate actual mass emissions. This default should only be used if there is no other available control efficiency.

A range of factors influence the dust generation from TSFs, including:

- moisture content;
- salt concentration;
- vegetation cover and organic matter (lichens, moss etc);
- surface structure (structural & textural cracks & inhomogeneity);
- traffic (mechanical and animals); and
- weathering.

(Carras, 1998)

Retaining a wet surface on TSFs will prevent dust generation (BPEMIM, Tailings Containment, 1995), while TSFs with a low salt content (and a low moisture content) have a greater potential for dust generation than TSFs with a high salt content. Revegetation of decommissioned TSFs will minimise their potential for dust generation.

The potential for TSFs to generate dust should be assessed on a facility basis. The assessment should be based on known factors, which influence dust generation and observational/monitored results.

In the absence of facility-specific the following assumptions may be made:

- zero dust generation from TSFs where hyper saline water used in process
- zero dust generation from 'wet' area of TSFs
- zero dust generation from vegetated TSFs

Alternative dust EETs include Direct Measurement

6.4 Metals in Dust

PM₁₀ and TSP may contain a metal fraction, which will represent part of the facility's metals emissions.

The speciation of dust, both PM₁₀ and TSP, using an emission factors approach may be achieved using:

- Metals content of ore (generic or facility-specific)
- Dust generation estimates (either through emission factors, modelling or direct monitoring)

The metals fraction for all processing dust sources may be assumed to be the same as that for unprocessed ore, in the absence of more suitable data. Fractions may be sourced from facility-specific assays of generic ore types (Appendix A).

Table 4 - Emission Factors for Dust Generation

Operation/Activity	TSP Emission Factor	PM ₁₀ Emission Factor	PM ₁₀ /TSP Ratio	TSP Emission Factor	PM ₁₀ Emission Factor	PM ₁₀ /TSP Ratio	Units	Emission Factor Rating
	High Moisture content ores			Low moisture content ores				
Primary crushing	0.01	0.004	0.4	0.2	0.02	0.1	kg/t	C
Secondary crushing	0.03	0.012	0.4	0.6	NDA		kg/t	D
Tertiary crushing	0.03	0.01	0.33	1.4	0.08	0.06	kg/t	E
Wet grinding (milling)	0	0		0	0		kg/t	
Handling transferring and conveying	0.005	0.002	0.4	0.06	0.03	0.5	kg/t	C
Loading stockpiles *	0.004	0.0017	0.42	0.004	0.0017	0.42	kg/t	U
Unloading from stockpiles *	0.03	0.013	0.42	0.03	0.013	0.42	kg/t	U
Loading to trains *	0.0004	0.00017	0.42	0.0004	0.00017	0.42	kg/t	U
Miscellaneous transfer points *	0.009	0.0038	0.42	0.009	0.0038	0.42	kg/t	U
Wind erosion (including stockpiles & TSFs) *	0.4	0.2	0.50	0.4	0.2	0.50	kg/ha/h	U

(Source: *EET Manual for Mining*) * High and low moisture content emission factors assumed as equal

Note:

- NDA - No data available
- Generally a high-moisture ore is taken to be one which either naturally, or as a result of additional moisture at the primary crusher (usually), has a moisture content of more than 4% by weight.
- Estimated Control Efficiencies For Various Control Measures:
 - 30% for windbreaks
 - 50% water sprays to keep ore wet
 - 65% for hooding with cyclones
 - 75% for hooding with scrubbers
 - 83% for hooding with fabric filters
 - 100% enclosed or underground
- Controls are multiplicative. For example, water sprays used in conjunction with wind breaks give an emission which is which is $[(1 - (50/100)) * (1 - (30/100))] = 0.35$ of the uncontrolled emission (ie. 50% of 70% of the total uncontrolled emissions)

The metals (and cyanide) content of TSF dust emissions should be based on representative sampling of the TSFs surface matrix.

Alternative metals content of dust EETs include Direct Measurement

6.5 Sewage

The reporting threshold for Category 3 substances is unlikely to be exceeded at most facilities, however, it is the responsibility of each facility to determine whether they exceed the reporting threshold.

Based on the West Australian Water Corporation wastewater treatment design criteria, the per person per day loading of total nitrogen and phosphorus has been calculated. The data in Table 5 below has been applied to the NPI reporting thresholds to provide an indicative facility population that will result in exceedence of the reporting thresholds.

Table 5 - Indicative Pollution Figures for Wastewater NPI Threshold Tripping

	kg per person per day	Indicative facility population
Total Nitrogen	0.011	3736
Total Phosphorus	0.0025	3288

Derived from West Australian Water Corporation wastewater treatment design criteria.

Assumes: Annual dry weather flow of 200 litres per person per day
 Total nitrogen concentration of 55 mg/L (range of 40 – 70 mg/L)
 Total phosphorus concentration of 12.5 mg/L (range of 10 – 15 mg/L)
 365 days per year of N and P loading

Using standard sewage loading data for Total Nitrogen and Total Phosphorus, an estimation of Total Nitrogen and Total Phosphorus emissions may be made using the equation shown below:

$$\begin{array}{l}
 \text{Mass of} \\
 \text{total N or} \\
 \text{P emitted} \\
 \\
 \text{(kg)}
 \end{array}
 =
 \left[
 \begin{array}{l}
 \text{Average} \\
 \text{loading of} \\
 \text{N or P per} \\
 \text{person per} \\
 \text{day} \\
 \text{(kg / p / d)}
 \end{array}
 *
 \begin{array}{l}
 \text{Average} \\
 \text{number} \\
 \text{of} \\
 \text{personnel} \\
 \text{on site} \\
 \text{(p)}
 \end{array}
 *
 \begin{array}{l}
 \text{Number of} \\
 \text{days of} \\
 \text{loading to} \\
 \text{the sewage} \\
 \text{system} \\
 \text{(d)}
 \end{array}
 \right]
 *
 \begin{array}{l}
 \text{Efficiency} \\
 \text{of sewage} \\
 \text{treatment} \\
 \text{system}^1 \\
 \text{(\%)}
 \end{array}$$

¹ The efficiency of the sewage treatment system is defined as the ratio of the effluent Total N or P divided by the influent Total N or P. The value is specific for a given treatment plant and can be determined by sampling the influent and effluent streams.

Additional EETs are presented in the *EET Manual for Sewage and Wastewater Treatment*.

Alternative total nitrogen & phosphorus EETs include Direct Measurement

6.6 Combustion Emissions

The use of emission factors for estimating emissions from combustion has been extensively studied and may be used to provide a relatively accurate estimate of substance emission.

Reference may be made to the following manuals for combustion emission factors:

- *EET Manual for Fossil Fuel Electric Power Generation*
- *EET Manual for Combustion in Boilers; and*
- *EET Manual for Combustion Engines.*

6.7 Carbon Regeneration

Natural gas is generally used as the combustion source in carbon regeneration. The *EET Manual for Combustion in Boilers* may be used to estimate combustion emissions from carbon regeneration activities.

6.8 Fuel Storage

Volatile Organic Compounds (VOC) may be emitted from fuel storage areas and as a result of incomplete combustion (Section 6.6).

Guidance on the estimation of VOC, and other NPI substances, may be obtained from the *EET Manual for Fuel and Organic Liquid Storage*.

7.0 Modelling

Modelling may be utilised to determine the fate of substances emitted to the environment, including emissions to air and groundwater.

This EET may be of particular use for estimation of emissions of substances such as PM₁₀, cyanide and dissolved metals through TSFs seepage.

For cyanide and dissolved metals emissions from TSFs, modelling would be likely to have at least two components:

- the fate of the substance within the TSF; and
- the fate and transport of substances within groundwater.

Models may be very simple, based on minimal data and making broad based assumptions, or complex with factors for weather influences, chemical speciation and site-specific factors.

The complexity of a model will influence the accuracy of any emission estimations made using this method. Wherever possible, however, models should be verified by direct measurement under a range of conditions. With effective model verification, models may be factored to allow for site-specific influences, and significant influences may be included within the model itself.

7.1 Groundwater Modelling - Fates & Trajectories

Groundwater movement may be modelled to allow prediction of groundwater fates and that of any associated dissolved substances. Additionally, modelling will allow the temporal prediction of groundwater movement allowing the potential for the breakdown of substances within the groundwater or their in-situ adsorption to be estimated.

Groundwater models may be based on limited data such as calculated groundwater flow rates and direction, or contain in-depth data such as the geology and hydrogeology of the area. The complexity of models should be stated when used to estimate emissions in order to ensure that the error bands associated with the reported data are fully appreciated.

The fate of dissolved metals resulting from TSFs seepage would be suited to this approach.

7.2 Seepage from TSFs

Seepage from TSFs is generally accounted for as part of the design criteria and should not be viewed as a failure of the containment system.

Modelling of seepage from TSFs is recognised as an appropriate means of designing and operating TSFs. Models may be used to estimate emission of dissolved substances such as cyanide and metals.

There are many commercially available models available. Models include PC-SEEP, a two-dimensional unsaturated/saturated groundwater flow model (Mt Keith Nickel, 1996).

7.3 Cyanide

The fate of cyanide within TSFs is subject to continuing research by both industry and academia. Modelling the fate of cyanide within TSFs, including losses due to wind erosion, is an area of primary focus. Models are currently available although caution in their use is advised regarding the assumptions with respect to facility-specific aspects such as geochemistry, operation and construction of TSFs.

AMIRA are currently carrying out a research program (P497a) with the aim of developing a model that may be applied to all TSFs with a high level of complexity and accuracy. This project will be completed in June 2000.

Facilities may decide to apply existing models in order to allow estimation of emissions. While there will be inherent errors associated with these models, errors bands may be calculated and stated where data is reported.

8.0 Engineering Calculations

Engineering calculations may be used to estimate emissions from processes subject to rigid controls, such as where a substance is formed coincidentally (eg. carbon disulfide) or where the substance breaks down very quickly in the atmosphere such as nickel carbonyl.

These processes may be designed to operate at a given efficiency, and while variations will occur it may be valid to assume a given performance efficiency under normal operating conditions.

Engineering calculations also utilise standard physical and chemical laws and constants to allow the estimation of particular emissions. These may include equilibrium constants, thermodynamic properties of processes, chemical reactions, pressure constants and physical laws such as Boyle's Law.

Engineering calculations are based on known performance standards of particular processes and equipment, physical/chemical properties (eg. vapour pressure) of the substance and mathematical relationships (eg. ideal gas law).

9.0 Direct Measurement or Source Monitoring

Direct measurement (or source monitoring) is one of the more accurate methods of estimating emissions of substances from processes and facilities. A facility may wish to use existing monitoring data for NPI reporting and/or establish additional monitoring. As stated in Section 4.0, the NPI has a commitment of not requiring any additional monitoring.

Facilities may decide to undertake direct measurement in order to:

- estimate their emissions of particular NPI substances;
- verify estimates from alternative EETs; and
- provide supporting data for other EETs.

Where direct measurement is undertaken it is essential to ensure background levels are fully considered. Some areas will have significant background levels of NPI substances either as a consequence of adjacent activities (eg. TSP and PM₁₀) and as a consequence of the natural background levels (eg. metals in particular geological formations).

Additionally the immediate and long-term aim of the monitoring program should be decided in order to avoid unnecessary ongoing monitoring.

Facilities may have existing monitoring commitments and data that can be applied to the reporting requirements of the NPI. Potential sources of existing data are discussed in Appendix B.

Facilities may also have the analytical expertise on site to enable the monitoring and analysis of NPI substances to be undertaken in a more cost-effective manner.

Direct measurement data may be used to calculate actual loads to the environment by multiplying the concentration of the NPI substances in the final emission stream, by the volume of the final emission stream.

$$\begin{array}{ccccc} \text{mass} & & = & & \text{substance} & * & \text{volume of} \\ \text{emitted} & & & & \text{concentration} & & \text{total emission} \\ \text{(kg)} & & & & \text{(kg / m}^3\text{)} & & \text{(m}^3\text{)} \end{array}$$

Where direct measurement is undertaken it is essential that sampling and monitoring procedures are established. The procedures should ensure that all sampling and analyses are undertaken in a standard manner and in compliance with Australian, or other, standards.

9.1 Total Nitrogen and Total Phosphorus

Total nitrogen and total phosphorus loadings may be estimated by direct measurement based on:

- wastewater flows; and
- representative concentrations of total nitrogen and phosphorus in wastewater flows

Direct measurement is applied to 'end of pipe' emissions ensuring that the facility-specific efficiency of wastewater treatment plants are fully considered.

Alternative total nitrogen and phosphorus EETs include Emission Factors

9.2 Dust & PM₁₀

PM₁₀ emissions are estimated from their point of creation. As such the presence of a buffer zone will not influence the estimated emissions.

Direct measurement may be designed to monitor overall site emissions or emissions from particular processes. In all cases it will be important to ensure background levels are considered and factored into emission estimations.

Alternative PM₁₀, and TSP, EETs include Emission Factors and Modelling

9.3 Metals in Dust

PM₁₀ and TSP will contain a metal fraction. Speciation of PM₁₀ and TSP levels will be necessary to allow estimation of the facility's emissions of these metals.

Periodic analysis of dust samples will allow the speciation of dust with a greater level of accuracy.

The degree of dust speciation required will be determined by the range of substances for which the reporting threshold has been triggered. It is important to note that reporting of metals may be triggered by a number of categories but all triggered substances must be estimated from all sources for reporting purposes.

Alternative metal EETs include Emission Factors

9.4 Cyanide

In monitoring for cyanide it is essential to:

- clearly define the purpose of the monitoring;
- define the form of cyanide which is to be monitored (free, total, WAD, complexed);
- develop an appropriate sampling regime (including replicates and blanks); and
- ensure samples are effectively preserved and treated appropriately.

(Source: BPEMIM, Cyanide Management; Minerals Council of Australia, 1996)

A flow diagram detailing the fate of cyanide within the facility, and its form at all fate pathways, should be developed to ensure that:

- monitored data is appropriate; and
- cyanide stoichiometry is valid.

In-depth guidance in the development of a cyanide monitoring program should be sourced from the references above, process technicians and specialist laboratories.

Cyanides comprise a large class of organic and inorganic chemical compounds, which contain a chemical group comprising a nitrogen atom triply bonded to a carbon atom.

Of this class of chemicals only the inorganic cyanides are relevant to the mining industry (NPI reporting is for inorganic cyanide compounds).

There is a confusing assemblage of terms used in connection with cyanide toxicology. The commonly used generic names to describe the inorganic cyanides are listed and explained below:

Free cyanide - the cyanide ion (CN^-) and molecular hydrogen cyanide (HCN) which in aqueous solution dissociates to form the cyanide ion.

Simple cyanides - represented by the chemical formula $\text{A}(\text{CN})_x$, where A is an alkali (eg sodium) or metal and x is the valance of A. Those simple cyanides which dissolve in water, particularly alkali cyanides, dissociate to generate cyanide ions and molecular hydrogen cyanide in aqueous solution.

Complex cyanides - the complex alkali-metallic cyanides generally represented by the formula $\text{A}_y\text{M}(\text{CN})_x$, where A is the alkali or metal, y the number of alkali or metal atoms, M is the heavy metal (iron, cadmium, copper. etc) and x is the valance of A multiplied by y, plus the valance of the heavy metal. Complex cyanides which dissolve release the complex ion $\text{M}(\text{CN})_x$ rather than the cyanide ion. The complex ion may then undergo further dissociation releasing the cyanide ion.

Total cyanide - a toxicological meaningless analytical quantity frequently encountered in the literature on water quality. The analytical procedure usually involves strong mineral acid reflux/distillation using a catalyst to break down even the most stable of cyanides and thiocyanates which are orders of magnitude less toxic.

Weak acid dissociable (WAD) cyanide - an analytic quantity determined by less harsh stripping of cyanide from the compounds containing it than with the total cyanide determination. The WAD determination includes the ions from: free cyanide; cyanide of zinc and nickel complexes part of the cyanide from copper and cadmium complexes, but no ions from iron and cobalt complexes.
(Source: Minerals Council of Australia, 1996)

The NPI requires that inorganic cyanide compounds are reported. As such, **total cyanide** should be reported from the gold ore processing industry. However, as shown by the example in Appendix D, a number of different forms of cyanide may need to be monitored in order to achieve an estimate of emissions.

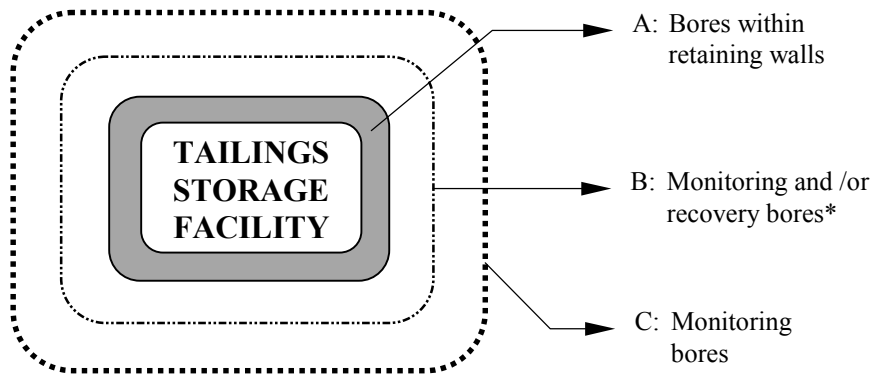
*Alternative cyanide EETs include Mass Balance,
Emission Factors and Modelling*

9.5 TSF Seepage

Seepage from TSFs may be estimated through the use of a system of monitoring bore holes.

Bore hole layout and depths will be dependent on facility-specific conditions, such as hydrogeology, depth to groundwater and groundwater flow direction. However, in order to achieve an accurate estimation of emissions, such as cyanide and metals, boreholes should:

- intercept known preferential flow paths; and
- be located at a range of distances from the TSFs.



* Alternative recovery systems, such as trenches, may also be used.

Figure 9 - TSF Bore Hole Monitoring Approach

NPI substances detected (above background levels) at bores 'B' (monitoring and/or recovery) will not be considered as emissions to the environment if recovered water is treated, for example pumping back to the TSF. The substances contained in the volume of water not recovered will be considered emissions to the environment.

NPI substances detected (above background levels) at bores 'C' (monitoring) will be considered as emissions to the environment.

The mass of NPI substances emitted will be estimated by multiplying the detected concentration at bores 'B' by the known hydraulic loading beyond bores 'B' (from the zone of influence and hydraulic conductivity of the soil) and the monitoring interval.

The hydraulic loading around the TSF is estimated using the equation below. The equation may be used to estimate the hydraulic loading from all 'faces' of the TSF (north, south, east and west) as a single entity or in distinct areas where the hydraulic gradient is known to differ significantly.

The hydraulic gradient is based on the hydraulic head produced by the TSF and the physical gradient between bores 'A' and 'B'.

$$\text{TSF Hydraulic Loading (m}^3\text{ / day)} = \text{Cross sectional area of zone of influence (m}^2\text{)} * \text{Hydraulic conductivity (m / day)} * \text{Hydraulic gradient}$$

The Emitted Hydraulic Loading is estimated by subtracting the volume of recovered water from the TSF Hydraulic Loading.

$$\text{Emitted Hydraulic Loading (m}^3\text{ / day)} = \text{TSF Hydraulic Loading (m}^3\text{ / day)} - \text{Volume of recovered water (m}^3\text{ / day)}$$

The emission of NPI substances is then estimated

$$\begin{array}{ccccccc} \text{Mass of substance} & = & \text{Concentration of} & * & \text{Emitted} & * & \text{Period} \\ \text{emitted} & & \text{substance in bores} & & \text{Hydraulic} & & \\ & & \text{'B'*} & & \text{Loading} & & \\ & & & & \text{(m}^3\text{ / day)} & & \text{(Days)} \\ & & \text{(kg / m}^3\text{)} & & & & \\ & & & & & & \end{array}$$

* Where 'total cyanide' concentration is not available from bores the 'total cyanide' concentration from TSF return water should be assumed.

*Alternative seepage from TSFs EETs include Emission Factors,
Modelling & Mass Balance*

10.0 Emission Factor Rating

Every emission factor has an associated emission factor rating (EFR) code. This rating system is common to EETs for all industries and sectors and therefore, to all Industry Handbooks. They are based on rating systems developed by the United States Environmental Protection Agency (USEPA), and by the European Environment Agency (EEA). Consequently, the ratings may not be directly relevant to Australian industry. Sources for all emission factors cited can be found in Section 12.0 of this Manual. The emission factor ratings will not form part of the public NPI database.

When using emission factors, you should be aware of the associated EFR code and what that rating implies. An A or B rating indicates a greater degree of certainty than a D or E rating. The less certainty, the more likely that a given emission factor for a specific source or category is not representative of the source type. These ratings notwithstanding, the main criterion affecting the uncertainty of an emission factor remains the degree of similarity between the equipment/process selected in applying the factor, and the target equipment/process from which the factor was derived.

The EFR system is as follows:

A	Excellent
B	Above Average
C	Average
D	Below Average
E	Poor
U	Unrated

Estimating your facility's emissions based on emission factors only, and without taking into account any control measures, may have an uncertainty as high as 100%.

Where emission factor ratings have not been included, these emission factors should be assumed to 'U', or unrated factors. This rating reflects the limited amount of research and data upon which the factors have been based, and/or the confidence associated with the factor itself.

11.0 Definitions

Reference should be made to the National Pollution Inventory and *The NPI Guide* for definition of terms used within the NPI system.

<i>Boundary</i>	Boundary is defined in varying ways depending on the emission type. For emissions to air boundary is the point of creation (such as the surface of a liquid during evaporation, or the wheels of a vehicle for dust generation). For emissions to land and water, boundary is the point at which a substance is no longer contained (such as a spill to ground from a process vessel, or a discharge to surface waters from a treatment works).
<i>Direct Measurement</i>	Technique used to estimate emissions to the environment through the sampling and analysis of emission streams.
<i>Emission</i>	Any release of substances to the environment whether it is in a pure form or contained in other matter. Emissions may be solid, liquid or gaseous.
<i>Emission Factor</i>	A number or equation that may be applied to raw data from a facility to estimate emissions from that facility without the need for emissions sampling and analysis. This technique is most often used to estimate gaseous emissions to the environment.
<i>Fugitive Emissions Inventory</i>	Emissions not released from a vent or stack. Means of recording usage and stores of all materials, and product, held on a facility or utilised by a process.
<i>Mass Balance Technique</i>	Estimation of emissions to the environment through equalisation of inputs and outputs to a particular process or facility.
<i>Power Generation</i>	Production of power for the operation of facilities and use in processes.

12.0 References

12.1 References Cited in Text

- BPEMIM, Tailings Containment, 1995
BPEMIM, Tailings Containment (1995), *Best Practice Environmental Management in Mining series, 'Tailings Containment'*, EPA
- BPEMIM, Cyanide Management, 1998
BPEMIM, Cyanide Management (1998), *Best Practice Environmental Management in Mining series, 'Cyanide Management'*, EPA
- Carras, 1998
Carras (1998), Letter to PPK Environment & Infrastructure, CSIRO
- Ellis, 1997
Ellis (1997), *Investigation & Modelling of the Natural Decay of Cyanide in a Gold Mine Tailings Pond*, Daniel Ellis, Honours Thesis, University of Western Australia.
- Heath et al, 1998
Heath et al (1998), *A method for measuring HCN_(g) emissions from CIP/CIL tanks*, CSIRO & Curtin University
- MERIWA Project M241, 1998
MERIWA Project M241 (1998), *'Saline Tailings Disposal & Decommissioning'*, Australian Centre for Geomechanics [ACG : 1004-98 (A)/(B)]
- Minerals Council of Australia, 1996
Minerals Council of Australia (1996), *Tailings Storage Facilities at Australian Gold Mines*
- Mt Keith Nickel, 1996
Mt Keith Nickel (1996), *Mt Keith Nickel Project Tailings Storage Upgrade CER*, Jan 1996, for WMC by Woodward Clyde
- NOI Guidelines, 1993
NOI Guidelines (1993), *Guidelines for preparation of a "Notice of Intent" - tailings disposal facility, vat leach, heap leach or extensions to existing structures*. WA DoME, July 1993
- Schulz, Roger, 1998
Roger Schulz (1998), Letter to NSW EPA and PPK Environment & Infrastructure
- Simovic, 1984
Simovic (1984), *Report on Natural Degradation of Cyanides from the Cullaton Lake Gold Mines Effluent*, Environment Canada, Waste Water Technology Centre.
NOTE: Referenced through Ellis, 1997
- Society of Mining Engineers, 1976
Society of Mining Engineers (1976), *Environmental problems of flotation reagents in mineral processing plant tailings water'*, Davis et al.
Flotation, A M Gaudin Memorial Volume, Society of Mining Engineers, M C Furstenen (Ed), 1976
- WMC Report Ref 692 634, 1992
WMC Report Ref 692 634 (1992), *Investigation of Engineering Design Criteria for Xanthate Handling Facilities*

12.2 References Not Cited in Text

Consultative Environmental Review Volume 1- Bulong Nickel Laterite Project, Kinhill Engineers, February 1996

Cyanide Management Guidelines, Department of Minerals and Energy, Mining Engineering Division, July 1992

Guidelines for Mining in Arid Environments, WA Department of Minerals and Energy, June 1996

Guidelines for the Preparation of an Annual Environmental Report, WA Department of Minerals and Energy, April 1996

Guidelines for the Safe Design and Operating Standards for Tailings Storage, WA Department of Minerals and Energy, March 1996

National Pollutant Inventory Homepage
<http://www.npi.gov.au>

Olympic Dam Expansion Project - Environmental Impact Statement, Kinhill Engineers, May 1997

Sodium Ethyl Xanthate - Full Public Report, National Industrial Chemicals Notification & Assessment Scheme.

Tailings Containment, Best Practice Environmental Management in Mining, Environment Protection Agency, June 1995

Technical Guidelines for the Environmental Management of Exploration and Mining in Queensland, Department of Minerals and Energy, January 1995

Waste Management: Solutions and Opportunities in the Mining Industry, 26th August 1993

The following Emission Estimation Technique Manuals referred to in this Manual are available at the NPI Homepage and from your local environmental protection agency (see the front of the NPI Guide for details):

- Emission Estimation Technique Manual for Combustion in Boilers;
- Emission Estimation Technique Manual for Combustion Engines;
- Emission Estimation Technique Manual for Fossil Fuel Electric Power Generation;
- Emission Estimation Technique Manual for Fuel & Organic Liquid Storage; and
Emission Estimation Technique Manual for Sewage & Wastewater Treatment.

Appendix A - Generic Ore Assays

Table A1: Generic Ore Assays

Element	Symbol	Basalt	Granite	Coal	Soil	Earth's Crust	Marine Clays	Marine Carbonates	Shale	Limestone	Sandstone	Sediment
Antimony	Sb	0.69	0.2	3.5	1	0.2	1	0.05	1.5	0.3	0.05	1.2
Arsenic	As	1.5	1.5	6.5	6	1.5	13	1	13	1	1	7.7
Beryllium	Be	0.3	5	1	0.3	2.6	2.6		3	<1	<1	2
Boron	B	8	12	70	20	10	230	55	130	20	30	100
Cadmium	Cd	0.13	0.09	0.2	0.35	0.11	0.21	0.23	0.22	0.028	0.05	0.17
Chromium	Cr	200	4	20	70	100	90	11	90	11	35	72
Cobalt	Co	35	1	5.4	8	20	74	7	19	0.1	0.3	14
Copper	Cu	90	13	15	30	50	25	30	39	5.5	30	33
Fluorine	F	510	1400	-	200	950	730	550	800	220	180	640
Lead	Pb	3	24	30	35	14	80	17	23	5.7	10	19
Manganese	Mn	1500	400	41	1000	950	6700	1000	850	620	460	770
Mercury	Hg	0.12	0.08	0.23	0.06	0.05	0.08	0.46	0.18	0.16	0.29	0.19
Nickel	Ni	150	0.5	15	50	80	225	30	68	7	9	52
Selenium	Se	0.05	0.05	2.9	7	0.05	0.17	0.17	0.5	0.03	<0.01	0.42
Zinc	Zn	150	240	31	90	190	150	20	160	20	220	150

(Source: EET Manual for Mining)

1. All figures in mg/kg (or g/tonne)
2. Extracted and adapted from Bowen, H.J.M. 1979. *Environmental Chemistry of the Elements*, Academic Press and generally checked against Berkman, D.A. 1989 *Field Geologists Manual*, The Australasian Institute of Mining and Metallurgy.
3. The figures listed above are average or median concentrations of the particular element within the rock or material specified.
4. The NPI requires the reporting of emissions of the elements listed in this Table and their compounds. As noted in the body of the Manual, it is recognised that trace metal analyses are not routinely undertaken for mining operations. In these situations, it is likely that the trace metal concentrations would be average to below average. Thus, where data on particular elements is not available, the average concentrations listed above for the particular material type should be used. In most cases, it would be expected that a low reliability would be attached to the emission estimate.
5. Further to Note 3, trace metal concentrations will be significantly greater than average where the reportable metal occurs at the site. For example, at a silver, lead and zinc mine, the concentrations of lead, zinc and probably cadmium in waste rocks, TSFs and soils will be significantly greater than the average concentrations listed in the above Table. It is expected that where it is necessary to use an assumed trace metal concentration to estimate emissions from a site, the facility will nominate a credible figure, which can be justified to the administering authority. The reliability attached to the estimate will generally depend on the data sets available from which the estimate has been calculated.

The table below presents the concentrations within the ore that will trigger the reporting threshold for Category 1 NPI substances.

Metal conc. in ore (ppm)	Annual tonnage (millions of tonnes)
0.1	100
0.2	50
0.3	33.3
0.4	25
0.5	20
0.6	16.7
0.7	14.3
0.8	12.5
0.9	11.1
1	10
10	1
100	0.1

Appendix B - Existing Data

Existing Data

The emission estimation methods proposed in this manual require best available data. This data may be available within a corporation or facility in a range of forms and sharing this data between facilities will aid reporting and allow for a greater level of accuracy in the estimation of emissions.

This data may be used to:

- directly estimate emissions;
- provide guidance on the most appropriate estimation methods to be used; and
- provide guidance on where direct monitoring may be most beneficially carried out.

It is not intended that facilities disclose proprietary or sensitive information, rather that this information is used in-house to assist in the NPI reporting process.

Data sources may include the following.

Existing Data & Research

Research projects of interest to industry are often sponsored, such as university PhDs and final year projects. These may be very directed areas of research, such as slag content and leachability or hydrogeological contamination, and may not be widely available within a facility or may be held at a corporate level.

Some mine sites currently address their dust emissions as three distinct components:

- the monitoring of ambient dust levels;
- the assessment of dust sources; and
- the implementation of dust control strategies.

Mine sites may also sponsor CSIRO dust research projects including that generated from TSFs.

Data of this type may be applied to emission estimations methods to increase their accuracy either directly through the development of emission factors or indirectly by identifying additional process within mass balances.

Mines may also have carried out discrete monitoring studies to determine the health or environmental impacts of particular substances. While these studies may have shown that minimal health or environmental risk is posed and hence ongoing monitoring is not required, it may also be used to allow more accurate estimation of NPI substances.

Many mines will have access to geotechnical data and groundwater data for the mine site from exploration work carried out in the past. This data may provide information on groundwater flows, the location of palaeochannels and other geological formations, and provide useful data for deciding the location and depths of any monitoring boreholes.

Process Monitoring

Elements of the process may be monitored regularly in order to optimise recovery of the product. This data may be applied to emission estimation methods such as mass balance, serving as a verification of the mass balance to that stage of the process and raw data.

Monitored areas may include:

- ore;
- concentrate; and
- TSFs water input and return

Monitoring may also be undertaken for health and safety requirements and may include:

- ammonia;
- cyanide;
- acids; and
- carbon monoxide

Licenses & Reporting

Mine sites may be required to carry out monitoring which can be applied to the requirements of the NPI. These data may include the following parameters:

- sulfur dioxide;
- sulfuric acid fumes;
- arsenic (As);
- dust and particulates;
- metals; selenium, antimony, beryllium, cadmium, lead, mercury, chromium, manganese, cobalt, copper, nickel, zinc;
- chemical spills, including cyanide; and
- dangerous goods licensing.

Facilities may monitor TSFs and storage ponds at regular intervals to ascertain reuse potential and treatment methods such as neutralisation. Where seepage from ponds and TSFs is suspected monitoring of bore holes may also be undertaken. Parameters may be expressed as soluble or total, and may include:

- pH;
- conductivity and TDS;
- standing water level; and
- metals.

This data may be used:

- directly where NPI substances are being monitored and reported;
- indirectly such as dust monitoring where speciation of the dust component may be required; and
- relationally where the ratio of a monitored parameter can be related to the emissions of an NPI substance.

Approvals Data

Gold mines may have Consultative Environmental Reviews (CERs), Public Environmental Reviews (PERs), Notifications of Intent (NOIs) or other approval documents, which contain a range of

facility characterisation and operational efficiency data. This may be applied to emission estimation methods to provide greater accuracy in reported data.

For example from March 1993 all proposal submitted to WA DoME require a detailed summary and list of commitments. The range of information must be reported under the guidelines (NOI Guidelines, 1993) including:

- properties of TSFs;
- TSF construction parameters;
- decant or under drainage systems;
- liner type; and
- monitoring.

Regulatory Data

Regulatory and government departments may hold extensive data relating to individual facilities, state and territories, or national and international sources. This data may be accessed to provide a more extensive database of available information with which to develop facility or corporate emission estimation strategies.

Suppliers

Suppliers should be able to provide in depth data regarding the fates of supplied chemicals within the process. A good example of this would be xanthates which breakdown to form carbon disulfide. Suppliers should be able to provide data relating to the proportional breakdown of xanthates, environmental stability, and potential for carry through in the gold process and to TSFs.

Inventory

A facility inventory may be used to identify all inputs to the gold process and the usage rates in relation to ore treated and product achieved. The inventory should be used as a tool to assist in the estimating and reporting process and will not need to be submitted with estimated emissions.

An *example* of an existing facility inventory is presented below.

INPUTS	<i>Units</i>	Jan	Feb	Mar	...	Dec	TOTAL
Tonnes of ore treated	<i>tonnes</i>						
Gold production	<i>kg</i>						
Sodium Cyanide	<i>tonnes</i>						
Quicklime (78% CaO)	<i>tonnes</i>						
(88% CaO)	<i>tonnes</i>						
Oxygen	<i>m3</i>						
Carbon	<i>tonnes</i>						
Flocculant	<i>tonnes</i>						
Antiscalant	<i>tonnes</i>						
Diesel	<i>litres</i>						
Grinding balls	<i>tonnes</i>						
Electricity	<i>kWh</i>						
LP Gas	<i>tonnes</i>						
Caustic soda	<i>tonnes</i>						
Hydrochloric acid	<i>tonnes</i>						
Potable Water	<i>kl</i>						
Bore Water Total	<i>kl</i>						
Decant Water from TSFs	<i>kl</i>						
TSF dewatering system	<i>kl</i>						
TSF decant return	<i>kl</i>						
TSF underdrainage	<i>kl</i>						

In addition to its use within the NPI framework a facility inventory may also be used to determine material usage across the site assisting in:

- financial planning;
- resource planning;
- waste minimisation; and
- environmental reporting.

It is likely that most facilities will have an inventory of some type and reference to this may enhance the accuracy of emission estimation and be applied to all emission estimation methodologies.

Appendix C - Transfers

Transfers

Transfers are the movement of NPI substances from the facility for 'processing' at another facility. For the gold industry these may include:

- all material sent to another facility for processing or use;
- all material to managed landfill or waste treatment sites outside of the facility; and
- all material leaving the facility to be reused, recycled, recovered, treated reprocessed or destroyed.

The reporting of transfers is not a requirement of the NPI at this stage. However, the concept of transfers is being trialed and may become a requirement of the NPI following the 1999 review. If transfers are to be estimated the appropriate EETs detailed in this manual should be used.

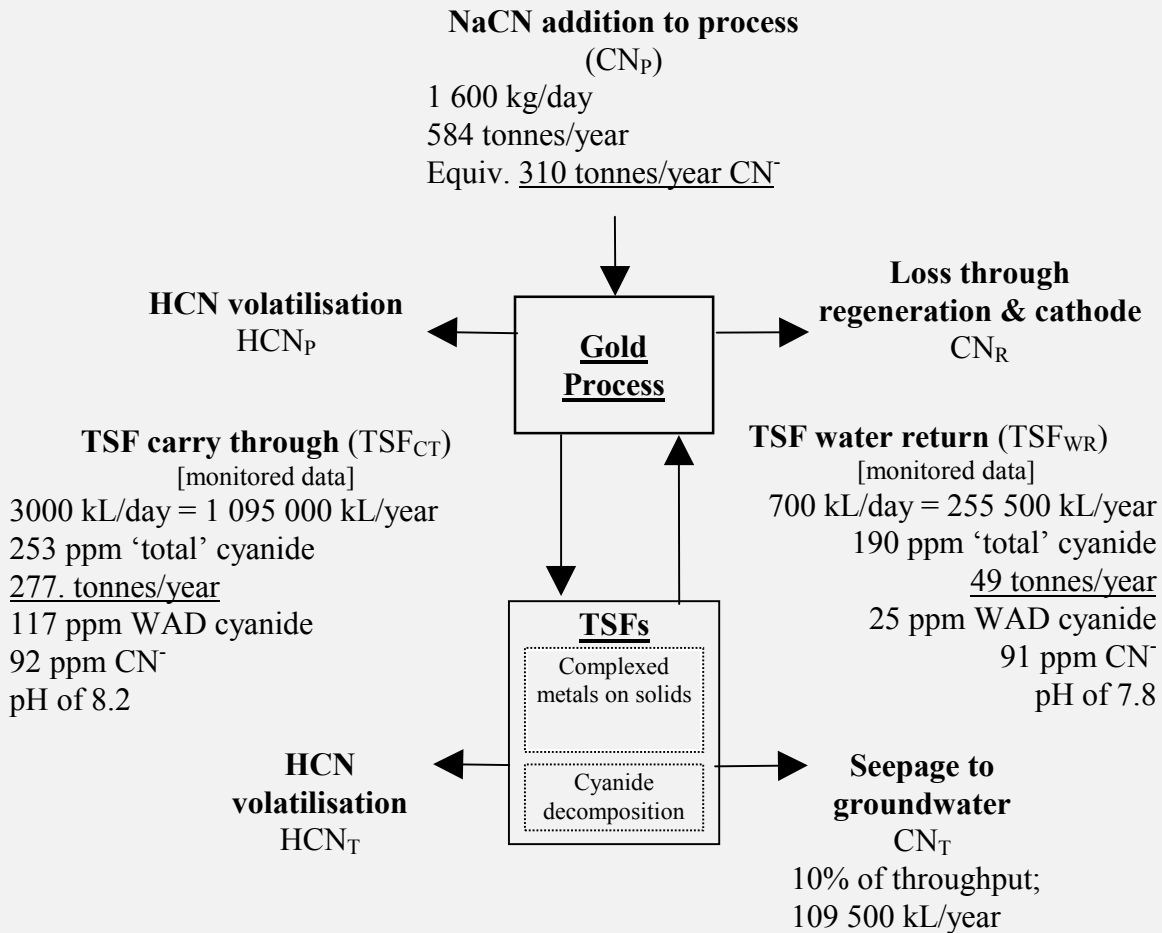
Examples of transfers of relevance to the gold industry, if included in the NPI, may include:

- Management of arsenic waste through its disposal at intractable waste sites.
- Transfer of sulfide concentrate between facilities. This may include transfer of material from the processing to an offsite roaster. In the same way the transfer of calcine from the roaster back to the processing plant is also a transfer. Where internal transfers take place, close liaison is likely to be required between facilities to prevent double accounting of emissions.
- Off-site disposal of wastewaters and sludge from treatment processes will represent a transfer.
- Off-site disposal of solid wastes will represent a transfer.

Appendix D - Example Emissions Calculations

Example 2 - Cyanide Emission

This example considers cyanide losses throughout the facility. The approach is largely based on mass balance, although emission factors and direct measurement are applied to provide an estimate of emissions.



HCN volatilisation

[Air Emission]

$$\begin{aligned} \text{HCN}_p &= 1\% \text{ of total cyanide (CN}^-) \text{ addition} \\ &= 310 * 0.01 = 3.1 \text{ tonnes of HCN} \\ &= \underline{3 \text{ tonnes of CN}^-} \end{aligned}$$

Loss through regeneration & cathode

[Air Emission]

$$\begin{aligned} \text{CN}_R &= (\text{CN}_P + \text{TSF}_{WR}) - (\text{TSF}_{CT} + \text{HCN}_P) \\ &= (310 + 49) - (277 + 3) \\ &= 359 - 280 \\ &= \underline{79 \text{ tonnes}} \end{aligned}$$

Example 2 - Cyanide Emission cont'

Cyanide loss to TSFs

$$\text{TSF}_{\text{CT}} - \text{TSF}_{\text{WR}} = 228 \text{ tonnes}$$

Seepage to groundwater

[Land Emission]

$$\begin{aligned} \text{CN}_{\text{T}} &= 109\,500 \text{ kL/ year} * 190\text{ppm} \\ &= \underline{21 \text{ tonnes}} \end{aligned}$$

HCN volatilisation

[Air Emission]

$$\begin{aligned} \text{HCN}_{\text{V}} &= (0.091 * 255\,500) * 0.8 \\ &= 18\,600 \text{ kg} \\ &= \underline{19 \text{ tonnes}} \\ &= \underline{18 \text{ tonnes CN}^- \text{ equivalent}} \end{aligned}$$

Cyanide emissions for reporting period

Inorganic Cyanide Compounds Emissions to Air:	<u>100 000 kg</u>
Inorganic Cyanide Compounds Emissions to Land:	<u>21 000 kg</u>
Inorganic Cyanide Compounds Emissions to Water:	<u>NIL</u>